

# MIDI observations of T Tauri stars and their companions



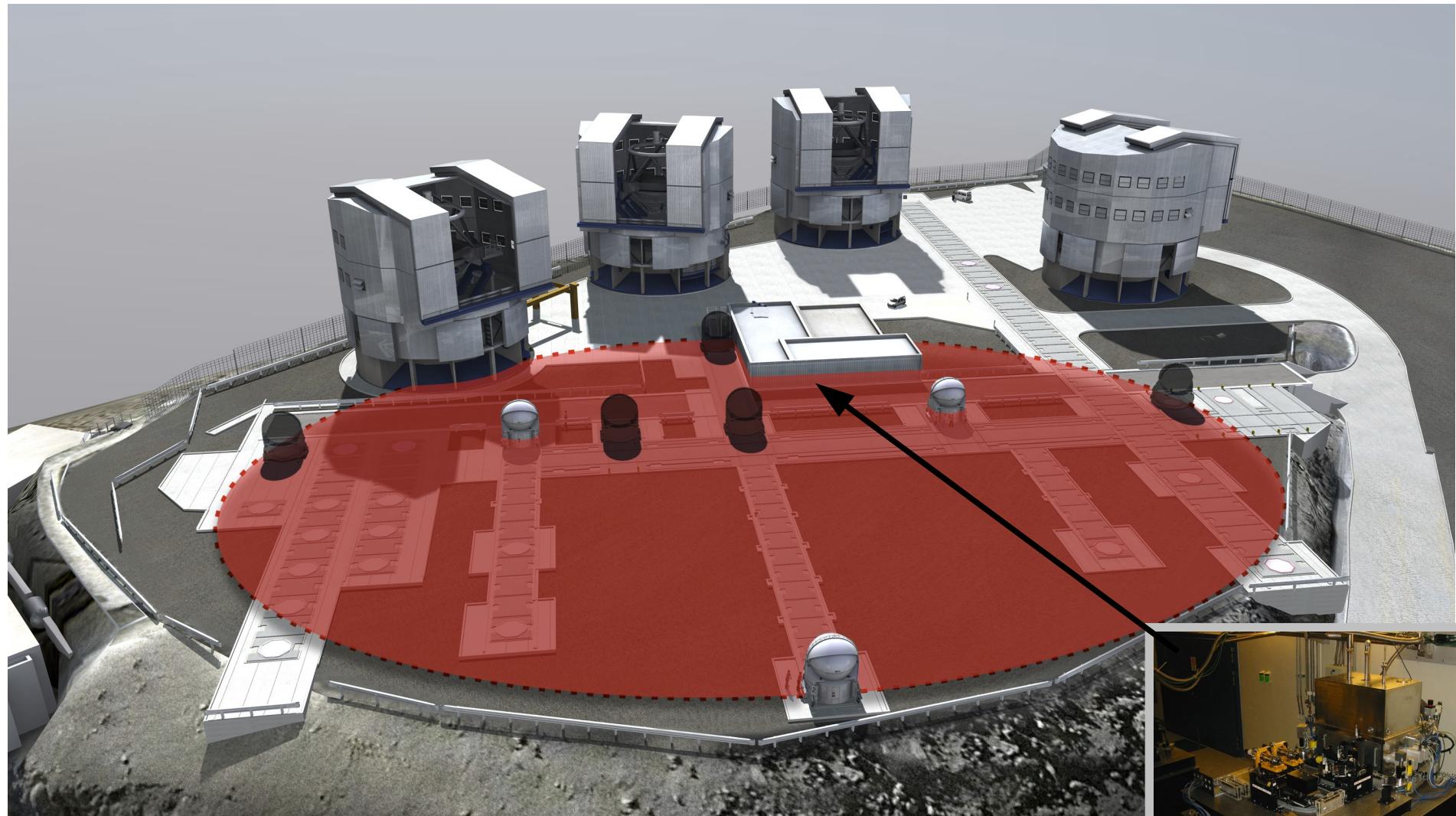
Introduction

# Observables

# The VLT Interferometer



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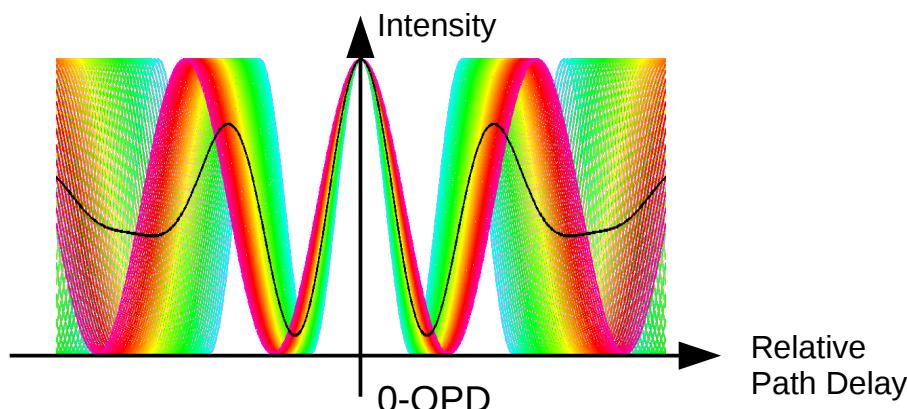


# Interferometric Observables

$$\frac{V_r(\vec{\rho})}{V_r(0)} = \frac{\int I(\vec{\alpha}) \exp(-i2\pi \frac{(\vec{\alpha} \cdot \vec{\rho})}{\lambda}) d\alpha}{\int I(\vec{\alpha}) d\alpha} \quad \text{← intensity}$$

$$V_{r,\text{norm}}(u, v) = \frac{\int \int I(\alpha, \beta) \exp(-i2\pi(u\alpha + v\beta)) d\alpha d\beta}{\int \int I(\alpha, \beta) d\alpha d\beta} \quad \begin{matrix} \text{↑} \\ \text{»visibility«} \end{matrix} \quad \begin{matrix} \text{↑} \\ \text{sky coordinates} \end{matrix} \quad \begin{matrix} \text{↑} \\ \text{spatial frequencies} \\ \text{in units of } B/\lambda \end{matrix}$$

»For sources in the far field the normalised value of the spatial coherence function is equal to the Fourier transform of the normalised brightness distribution  $I$ .« (van Cittert-Zernike Theorem)



## A) Fringe Contrast

sometimes known as »**Michelson visibility**«, and related to the measured maximum and minimum intensities in the fringe pattern:

$$V_{\text{Michelson}} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

visibility varies between 0 ( $I_{\min} = I_{\max}$ ) and 1 ( $I_{\min} = 0$ ); indicates »**compactness**« of the source

## B) Fringe Phase

location of the central fringe with respect to the zero optical path difference; indicates »**asymmetry**« of the source



Science I

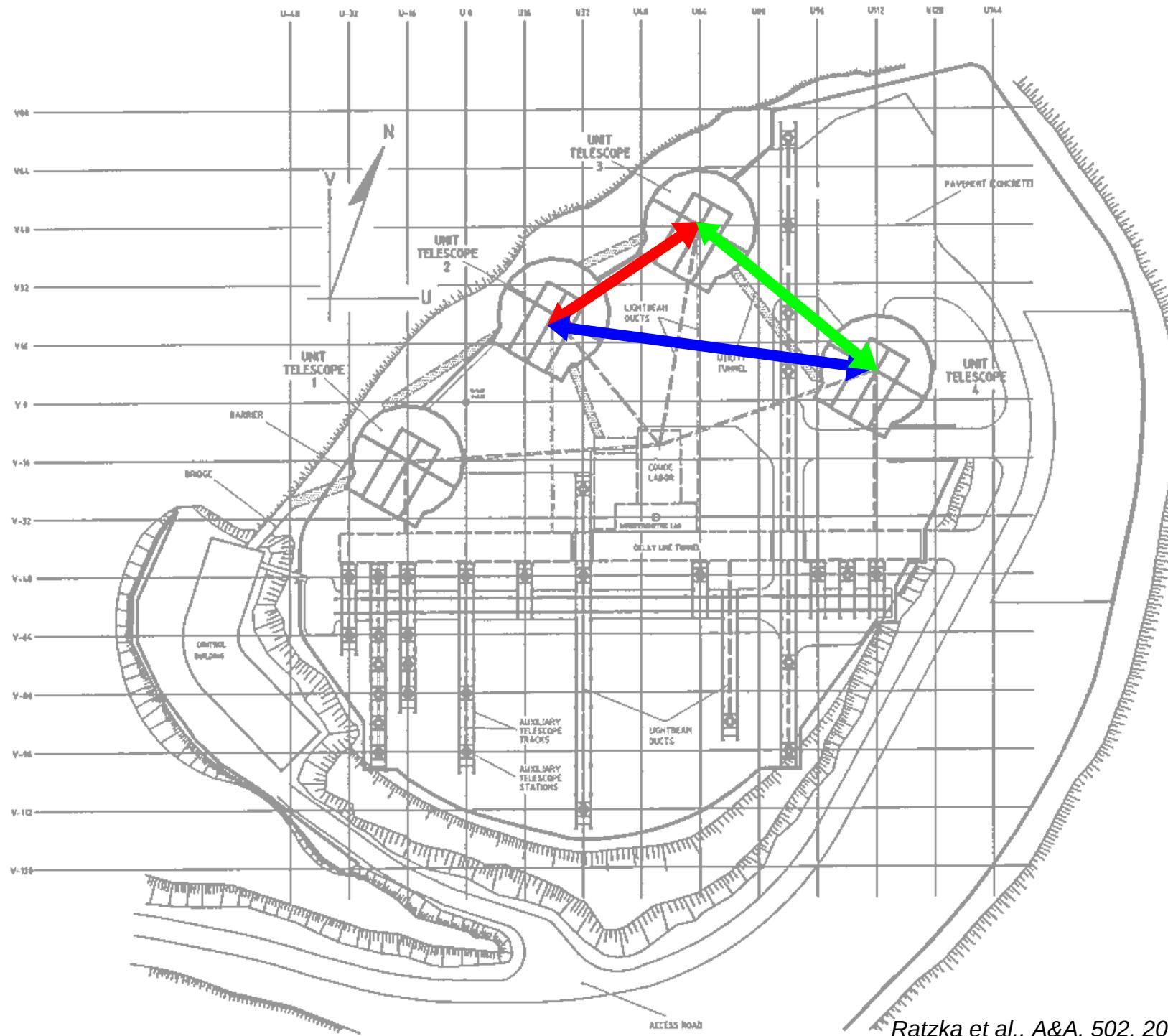
# **T Tauri – The Prototype**

# T Tauri - The Prototype

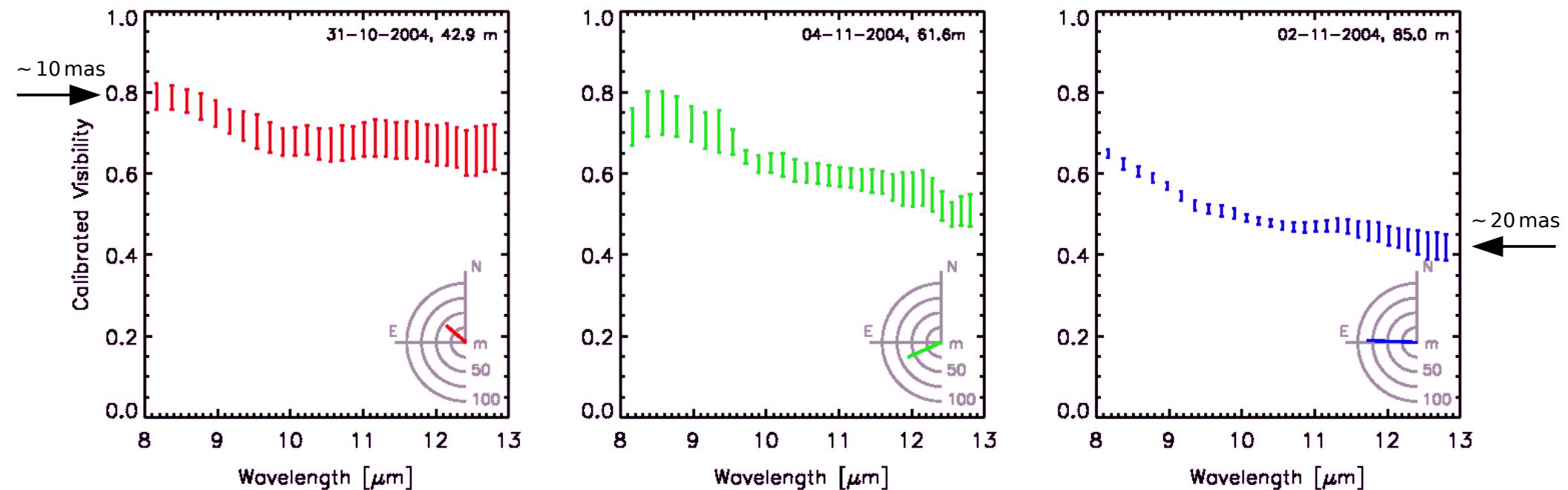


T. A. Rector (University of Alaska Anchorage) &  
H. Schweiker (WIYN and NOAO/AURA/NSF)

# The Grid



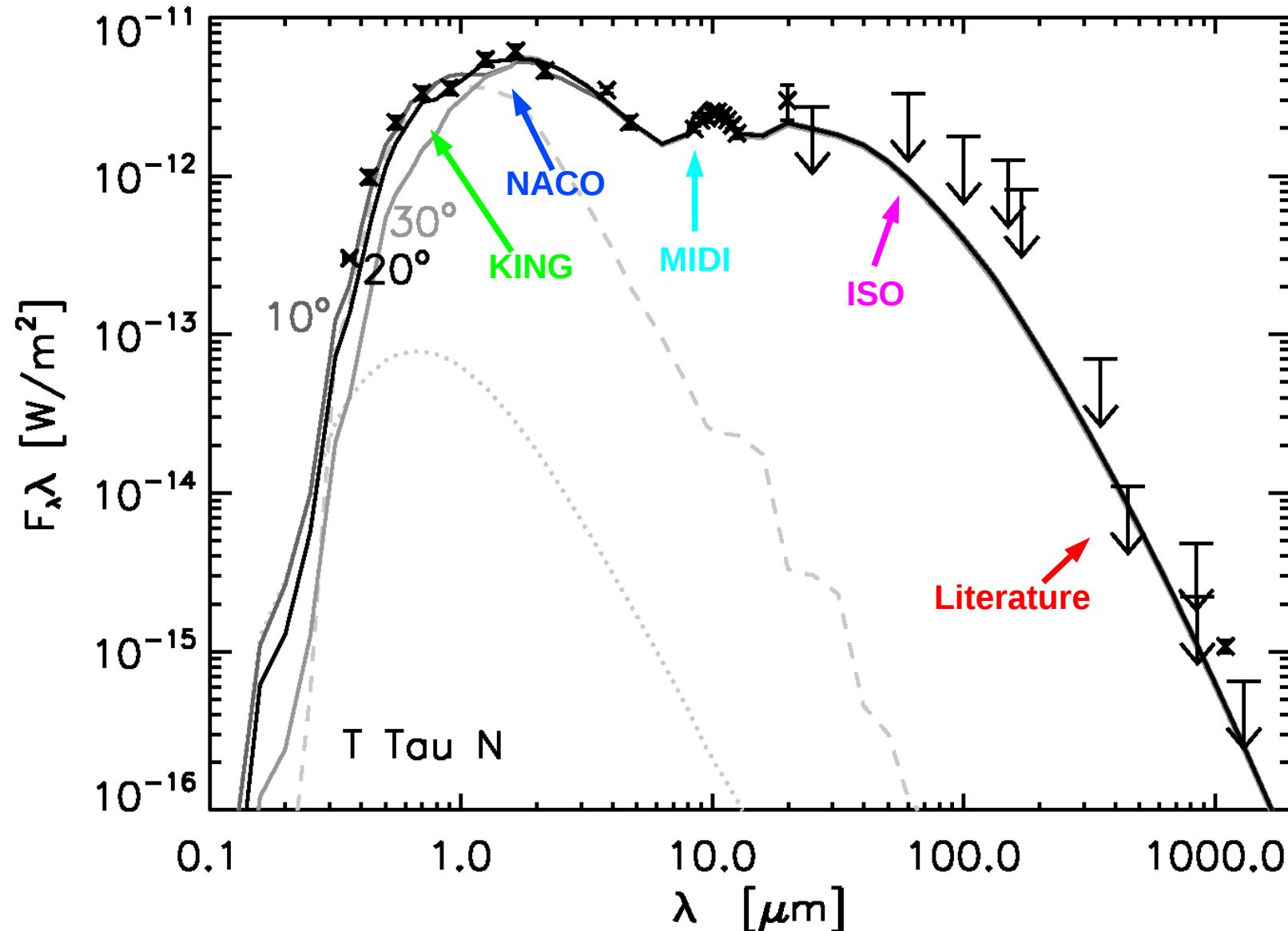
# The Visibilities ...



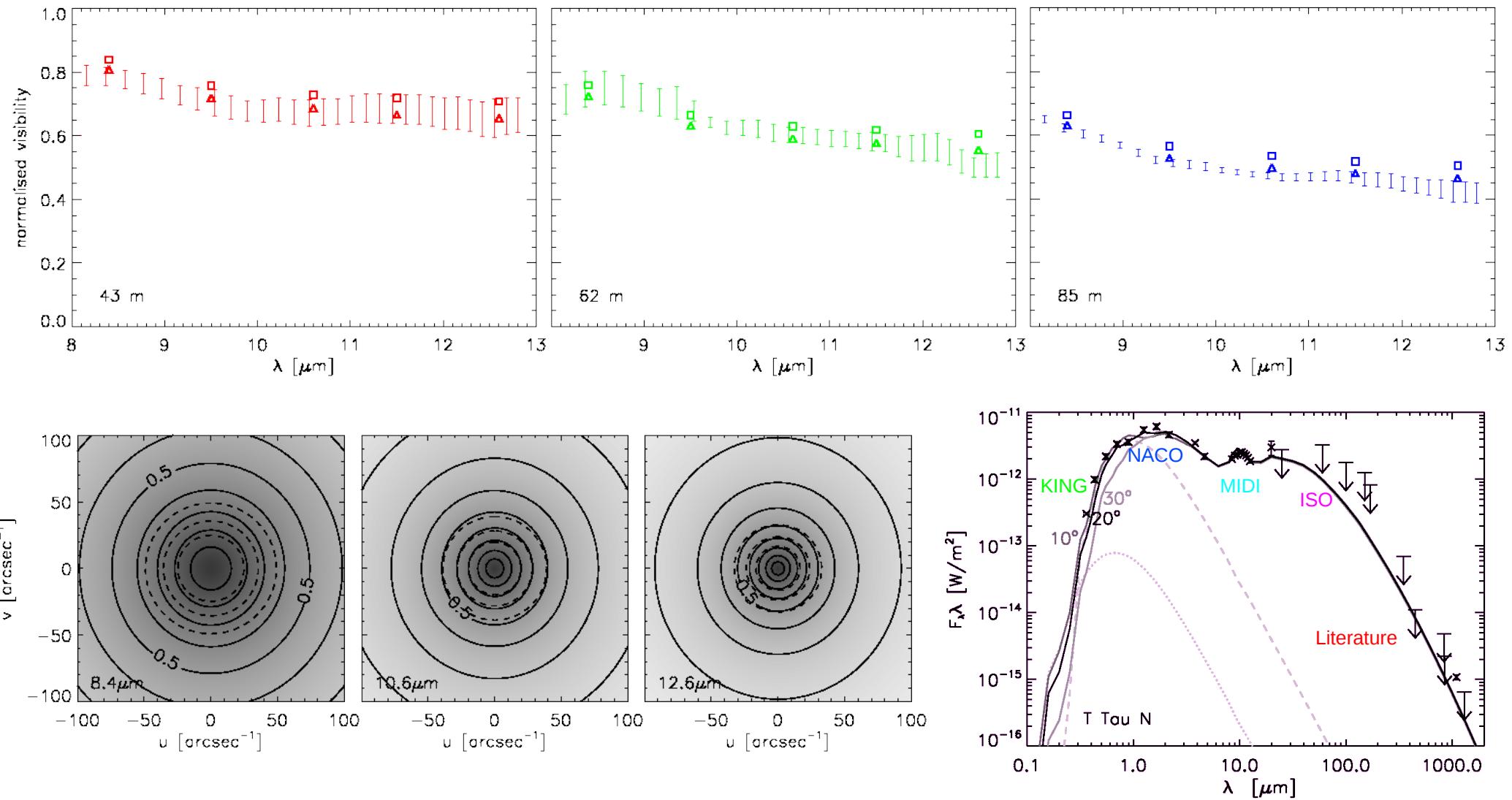
the resolution of the interferometer decreases with wavelength  
the emitting region becomes larger due to the temperature gradient

- ⇒ decreasing visibilities
- ⇒ direct size estimates

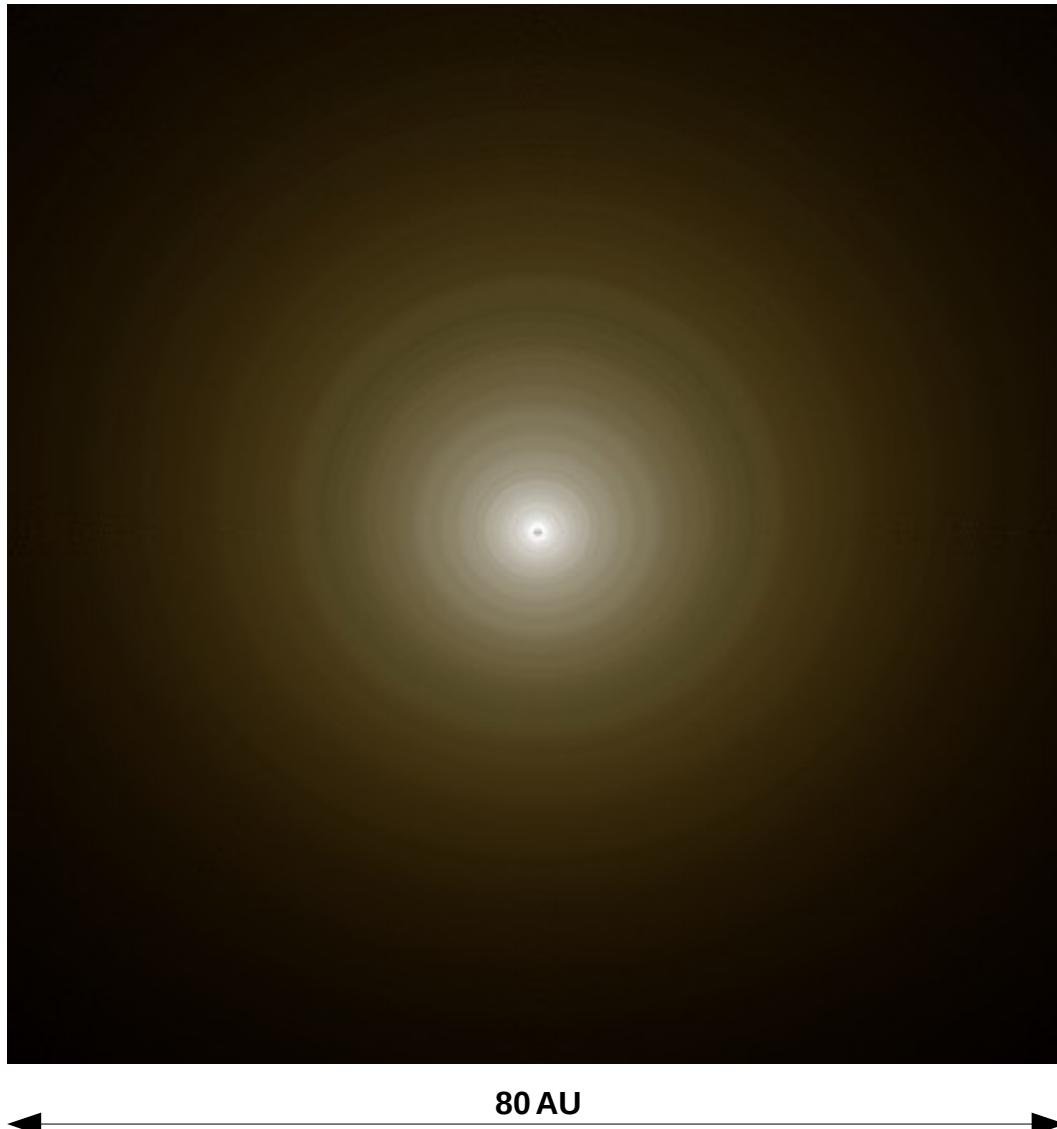
# The Spectral Energy Distribution ...



# The Radiative Transfer Model ...



# The Radiative Transfer Model ...



star

$$\begin{aligned}M_* &= 2.1 M_\odot \\T_* &= 5250 \text{ K} \\L_* &= 7.3 R_\odot \\R_* &= 3.3 R_\odot\end{aligned}$$

disk

$$\begin{aligned}M_d &= 0.04 M_\odot \\r_d &= 0.1 \dots 80 \text{ AU} \\i &< 30^\circ \\h_{100} &= 18 \text{ AU} \\\beta &= 1.25\end{aligned}$$

envelope

$$\begin{aligned}c_1 &= 1 \cdot 10^{-5} \\c_2 &= -5.0\end{aligned}$$

accretion

$$dM/dt = 3 \cdot 10^{-8} M_\odot \text{ yr}^{-1}$$

extinction (foreground)

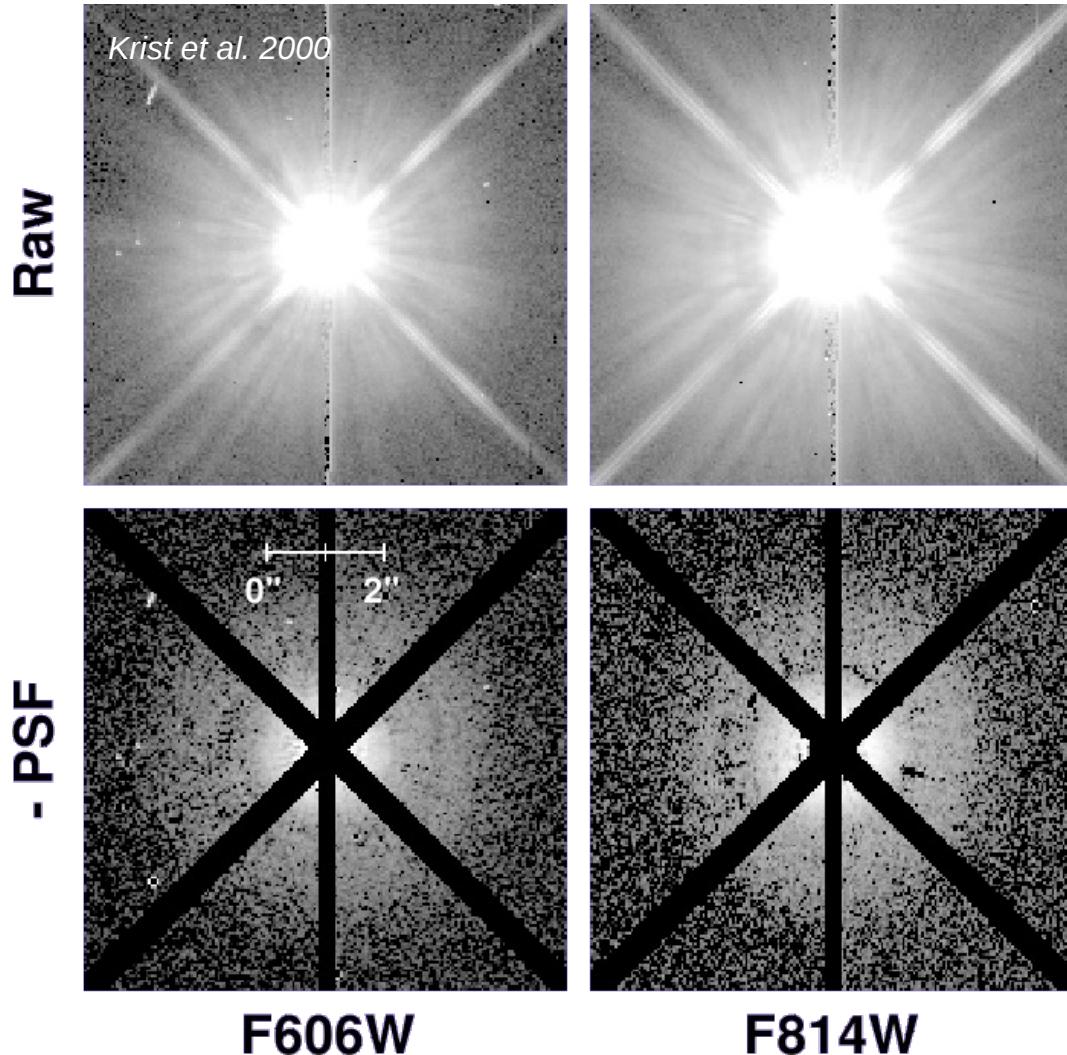
$$A_V = 1.5 \text{ mag}$$

A landscape photograph of a sunset or sunrise over a range of mountains. The sky is filled with warm colors, transitioning from deep orange and yellow at the horizon to a pale blue in the upper sky. The mountains are silhouetted against the bright sky. In the foreground, there's a dark, textured surface that looks like a paved road or a path through a field.

Science II

# **Structure of Transitional Disks**

# TW Hya - The Prototypical Transitional Disk



classical T Tauri star

distance of  $51 \pm 4$  pc

age of 5-15 Myr

K7V ( $T \sim 4000$ K,  $0.19 L_\odot$ )

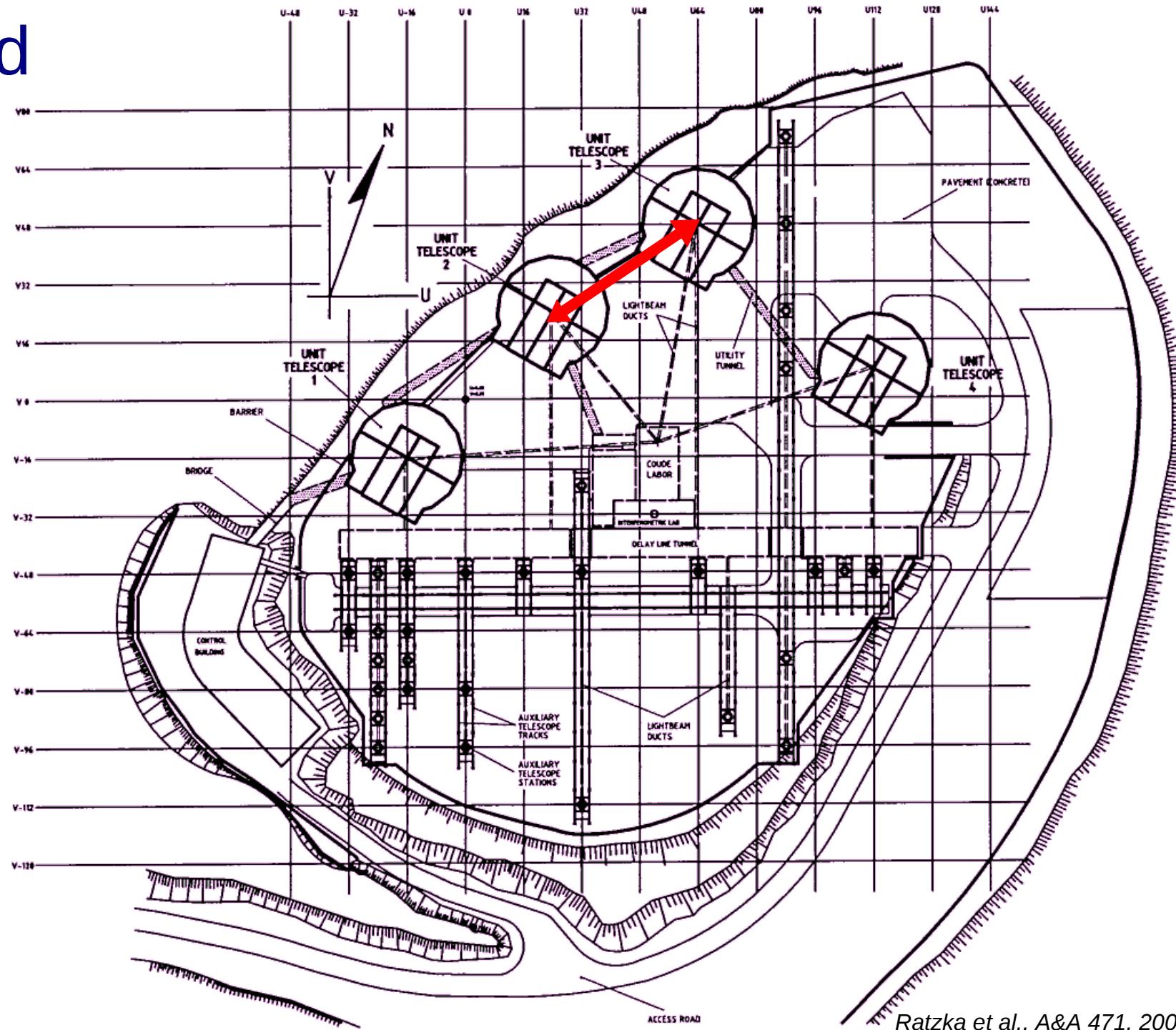
actively accreting at a low  
rate:  $4 \times 10^{-10} M_\odot/\text{yr}$

images taken at various  
wavelengths reveal a dust  
disk:

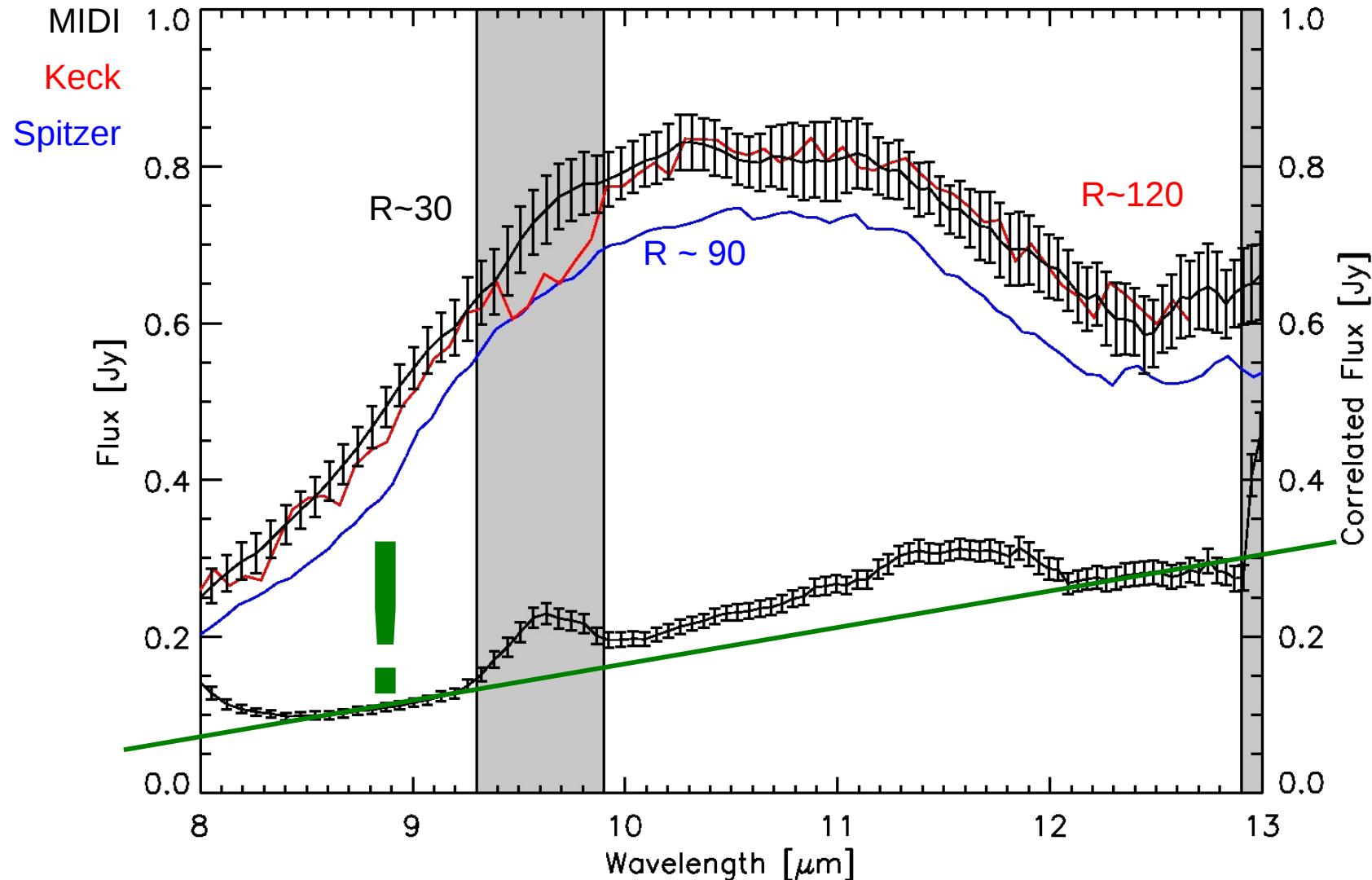
nearly face-on

diameter:  $\sim 300$ AU

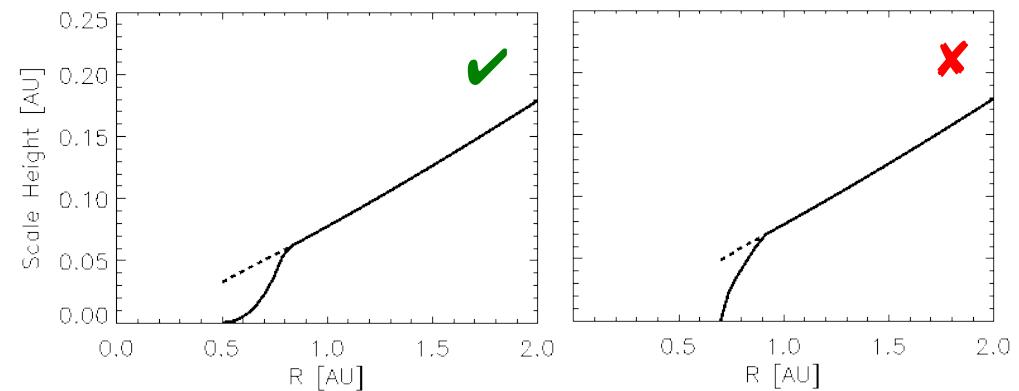
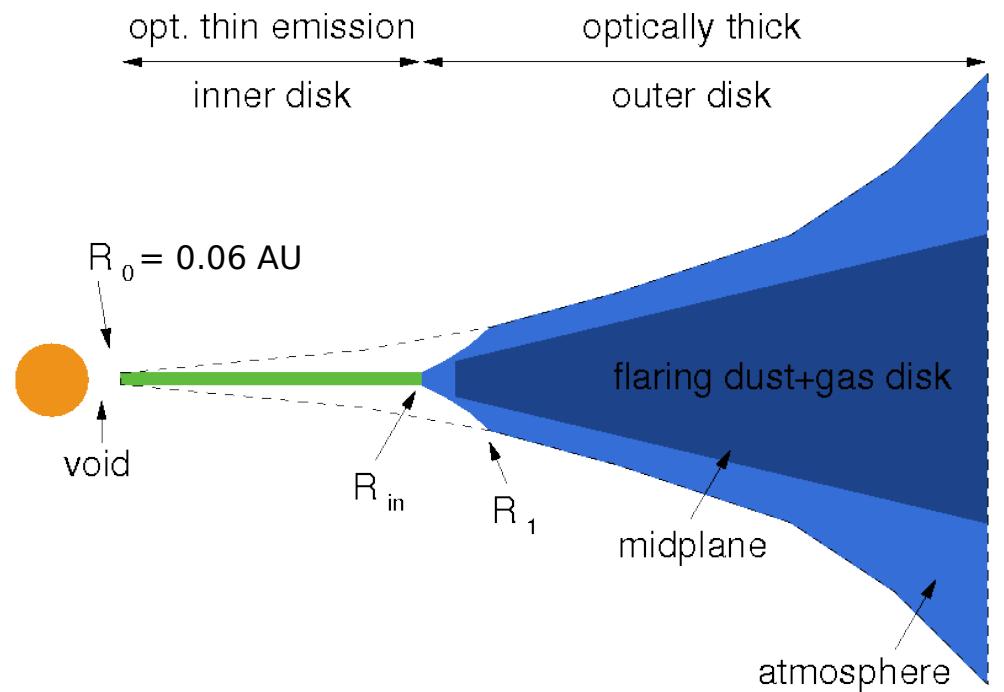
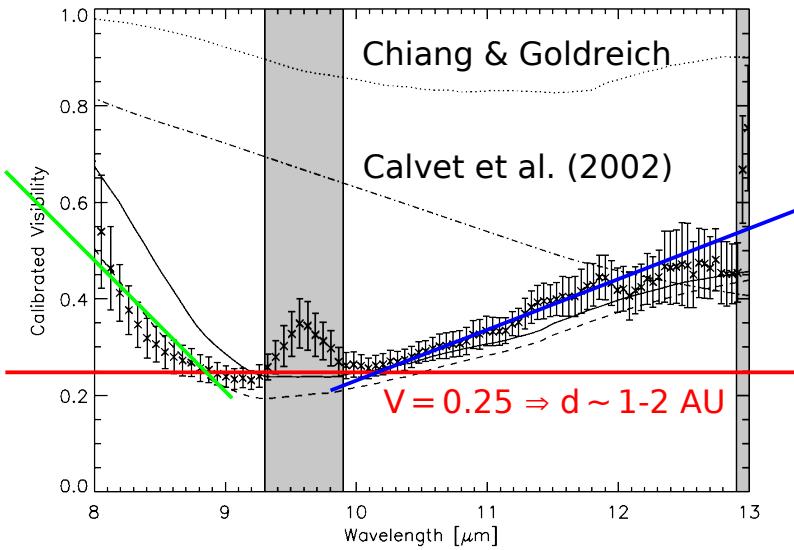
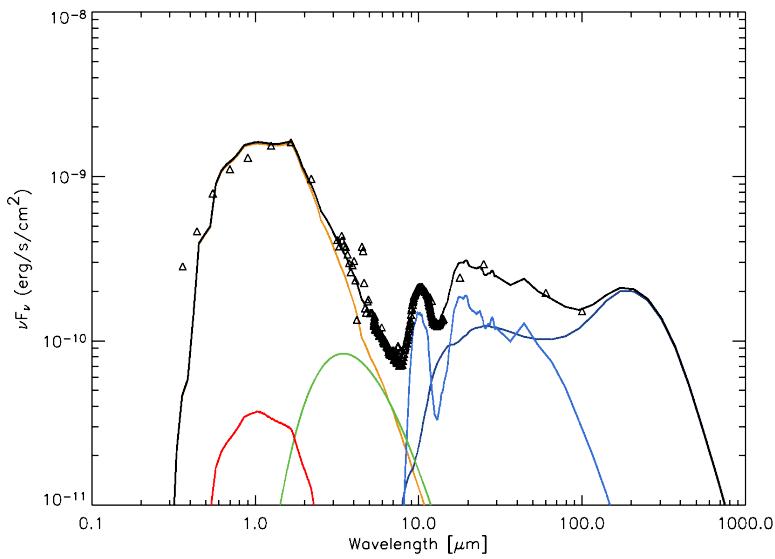
# The Grid



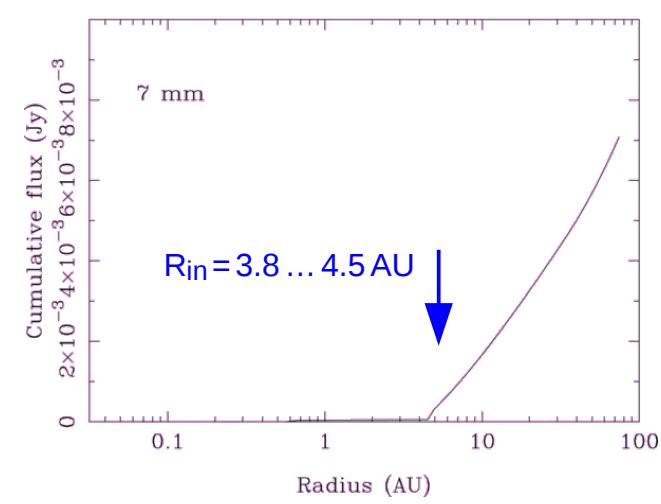
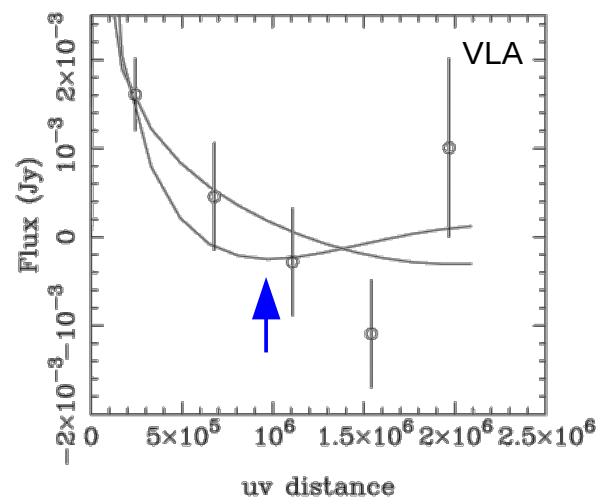
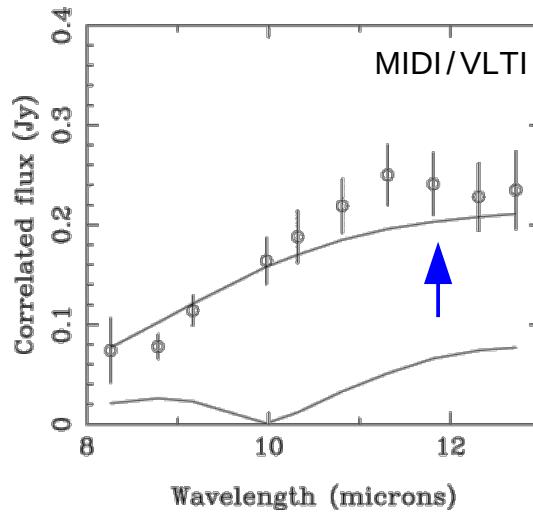
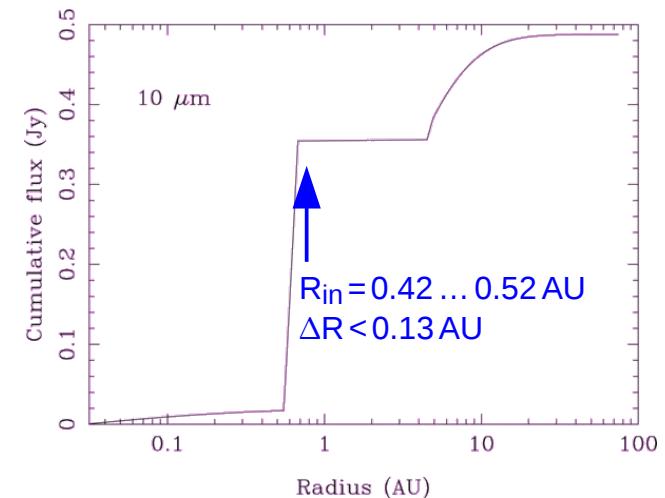
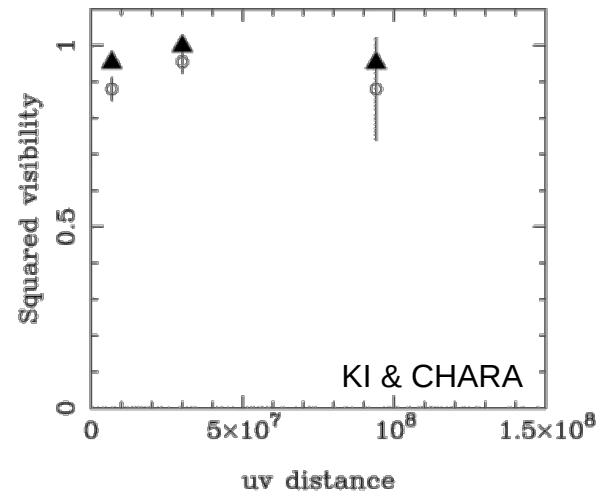
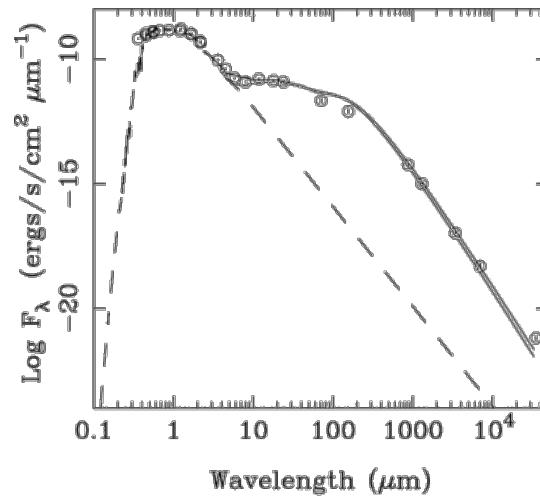
# The Total and the Correlated Flux



# Modified Chiang & Goldreich Model



# The Transitional Disk of TW Hya





Science III

# The Dust Composition and Distribution

# Dust Species and Properties

**Pyroxene Group**



**Olivine Group**



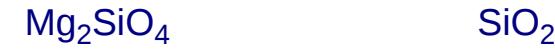
**Enstatite**



**Forsterite**



**Quartz**

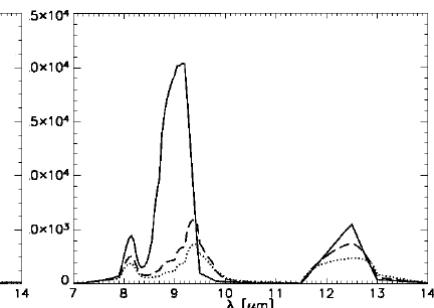
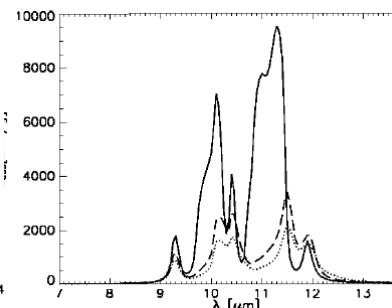
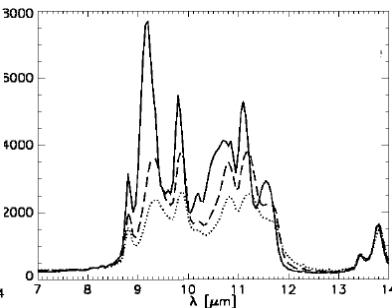
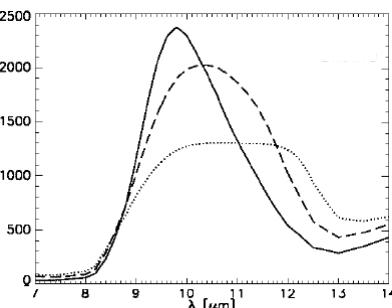
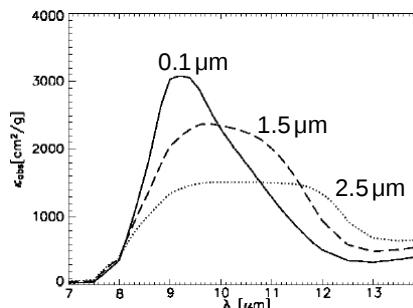


amorph

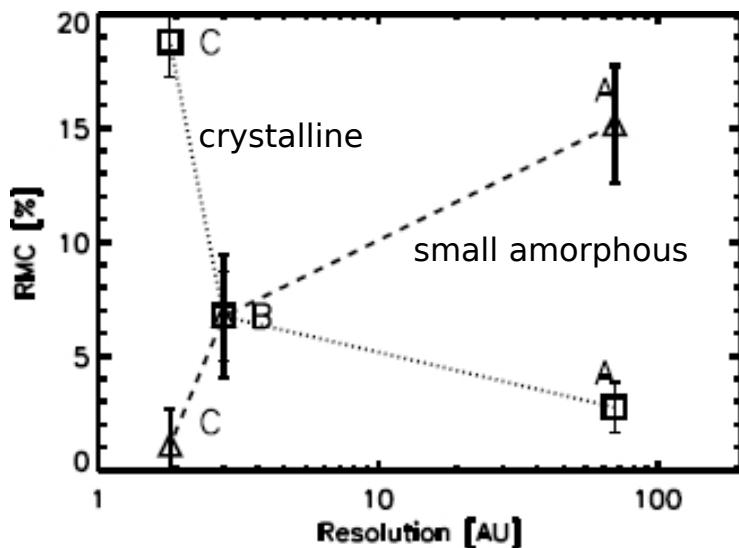
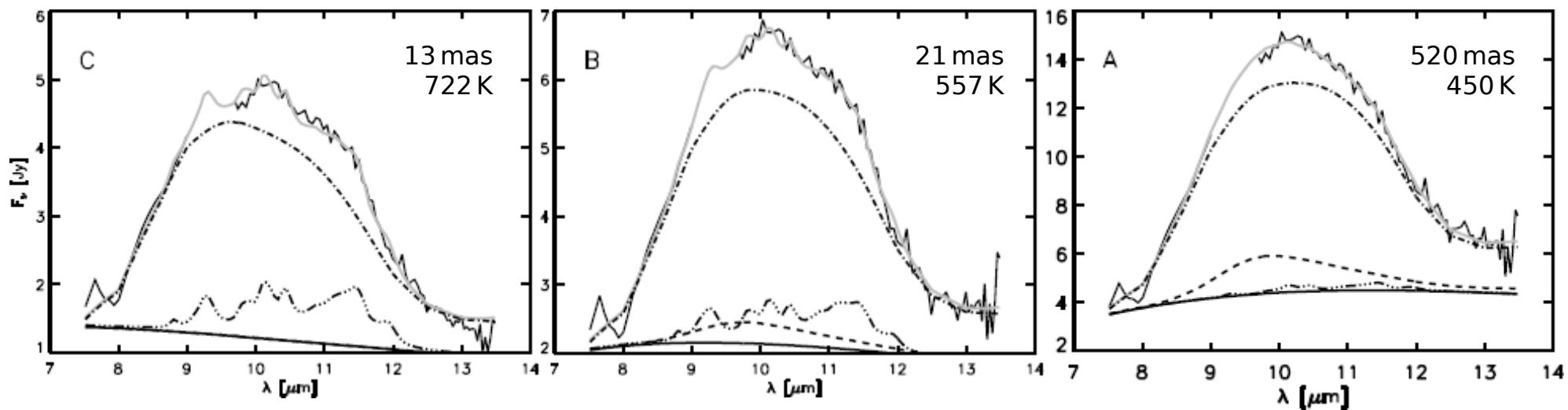
amorph



processing / thermal stability



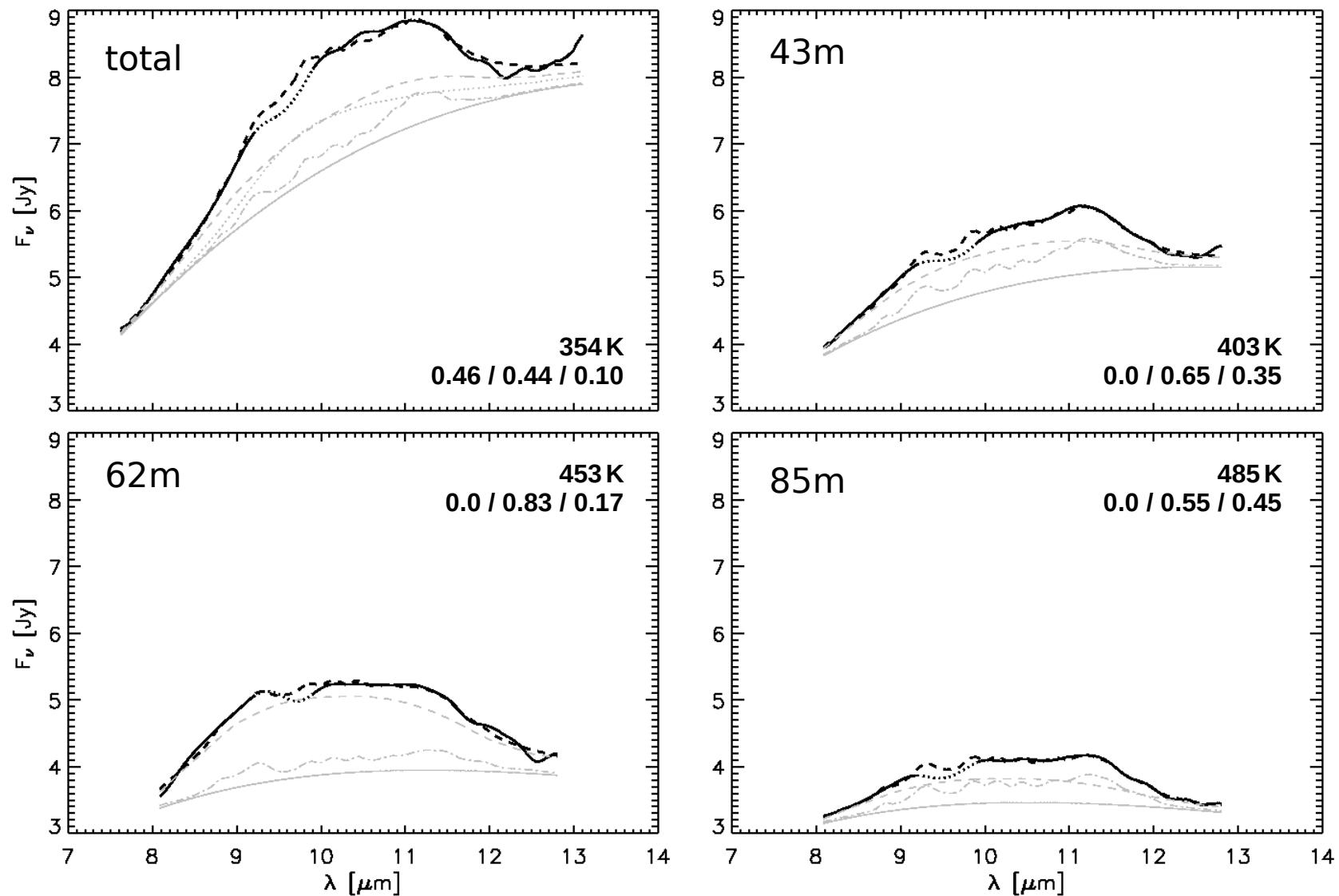
# Dust Processing in the RY Tau Disc!



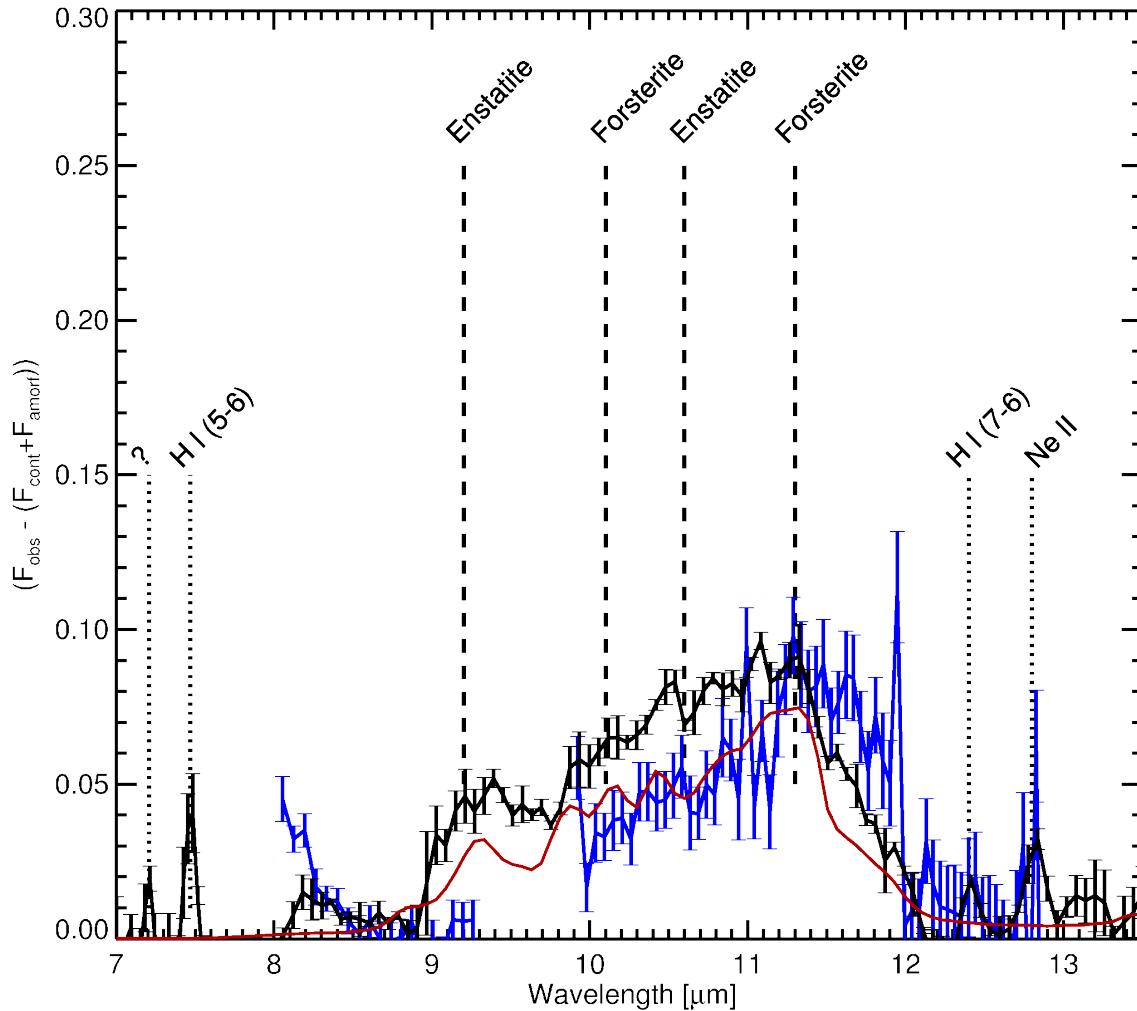
$$F_\nu = B_\nu(T_{\text{cont}}) C_0 + B_\nu(T_{\text{dust}}) \left( \sum_{i=1}^3 \sum_{j=1}^6 C_{i,j} \kappa_\nu^{i,j} \right)$$

Comparison of interferometric and single-dish observations shows for the first time dust evolution in a T Tauri star with a reduced fraction of small amorphous and an increased fraction of crystalline particles closer to the star.

# Dust Processing around T Tau?



# Where is the Processed Dust in TW Hya?

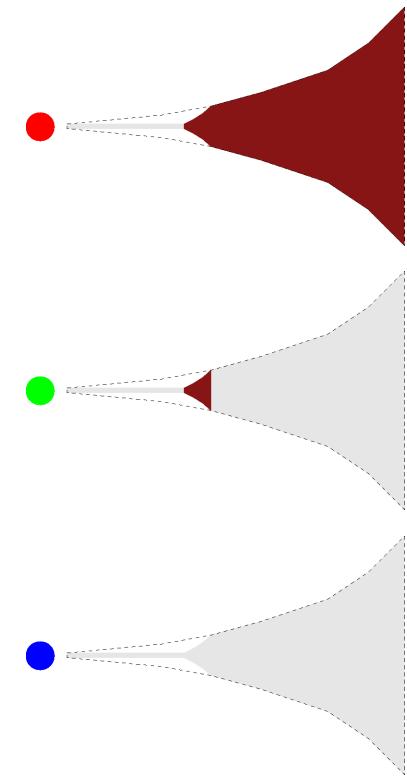
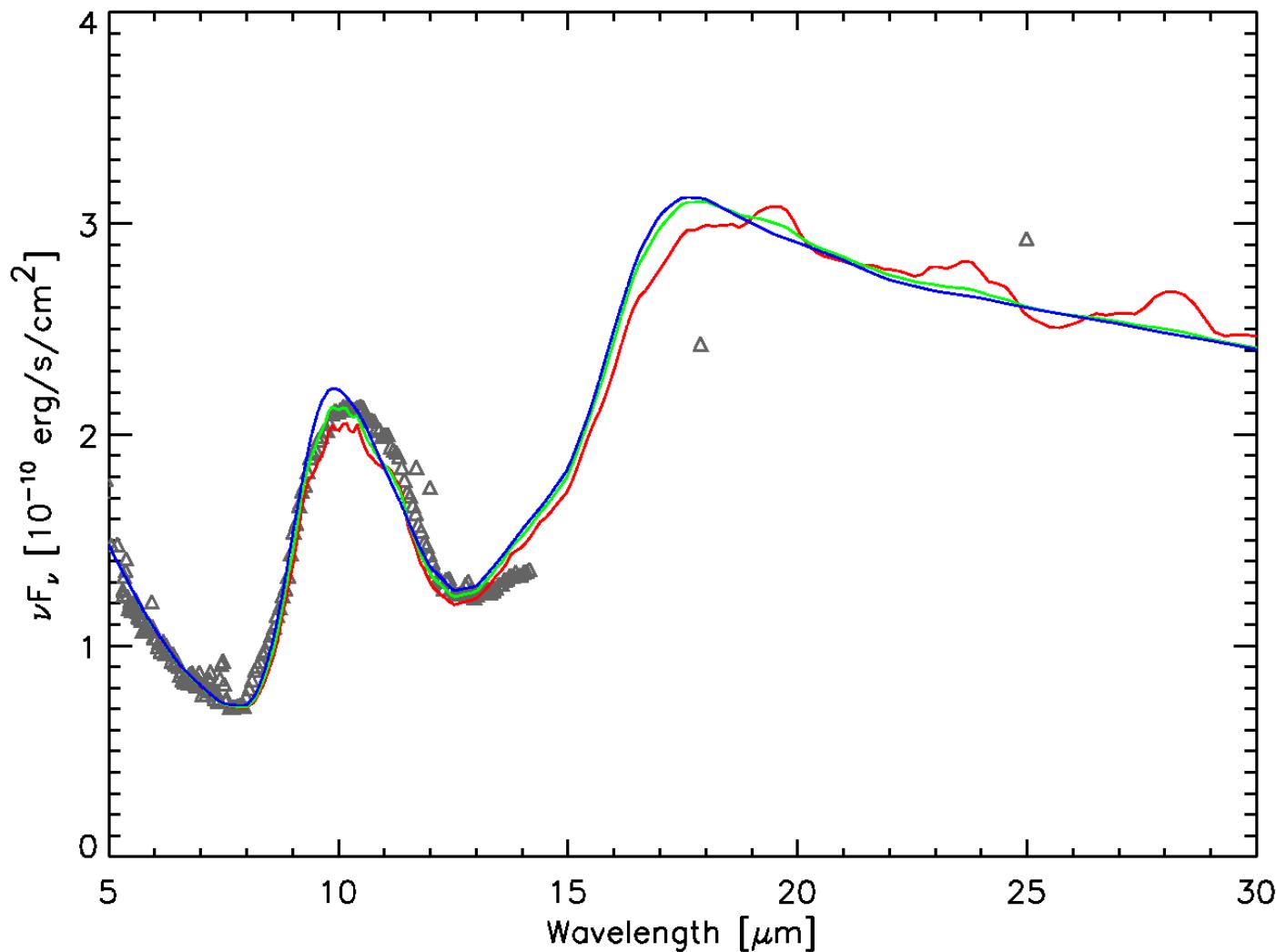


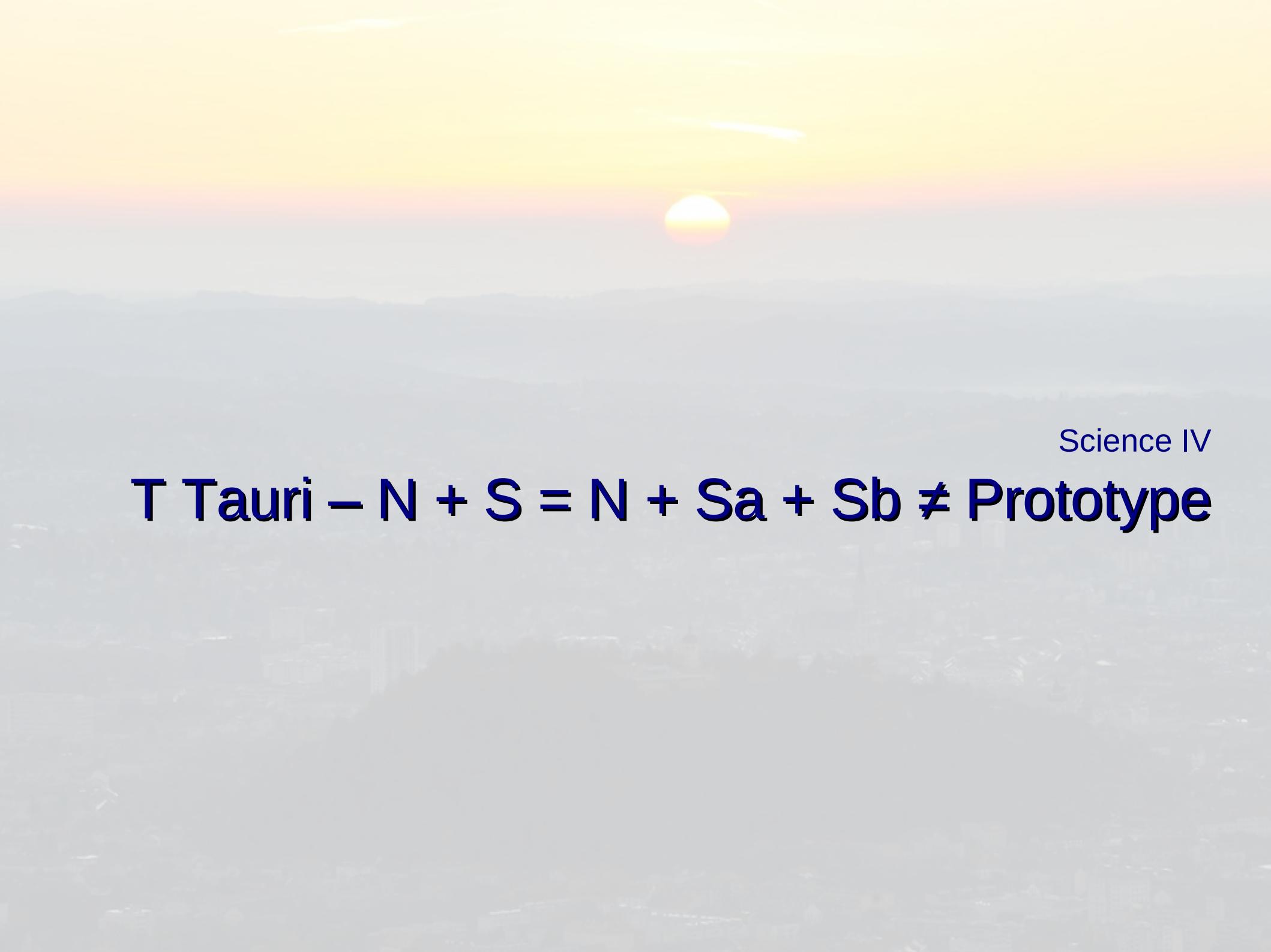
~ 8 % of the mass is in sub-micron sized crystalline dust particles; ~83 % of the mass is in sub-micron sized amorphous dust grains

Comparison of the spectrally dispersed correlated flux with the dust model shows that most of the crystalline material is concentrated within 1 AU from the central star

The disk of TW Hya is not well mixed

# Where is the Processed Dust in TW Hya?





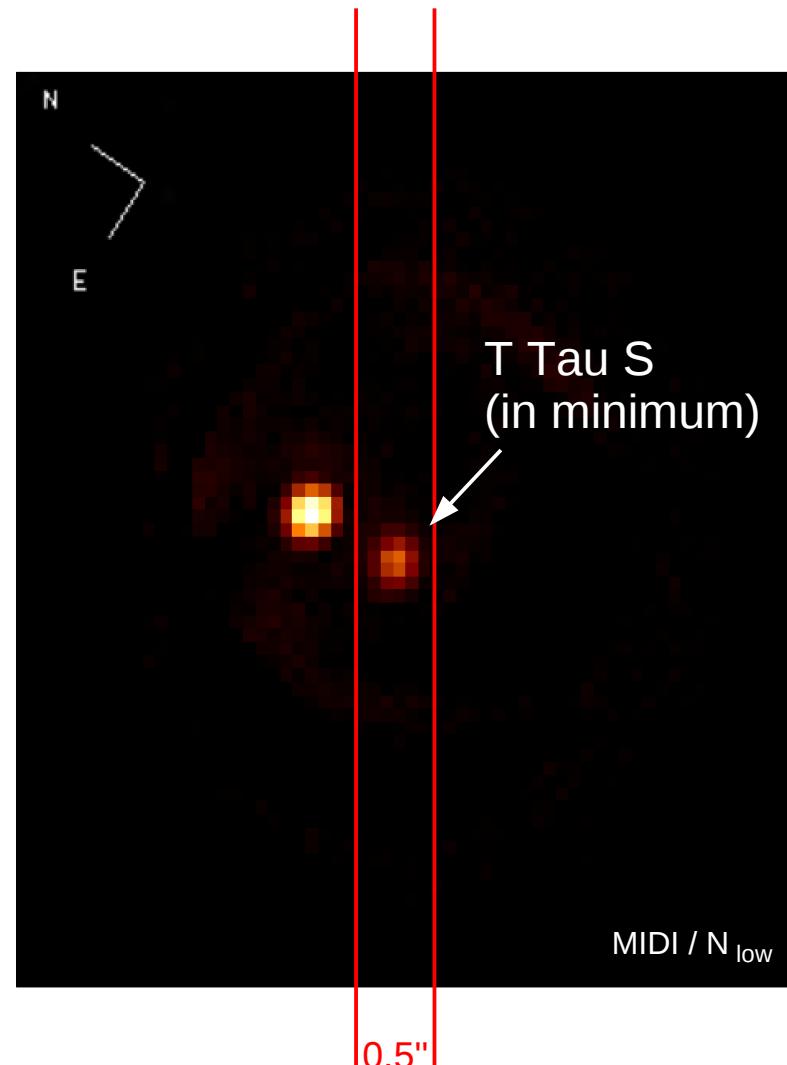
Science IV

**T Tauri – N + S = N + Sa + Sb ≠ Prototype**

# A Non-Prototypical Prototype



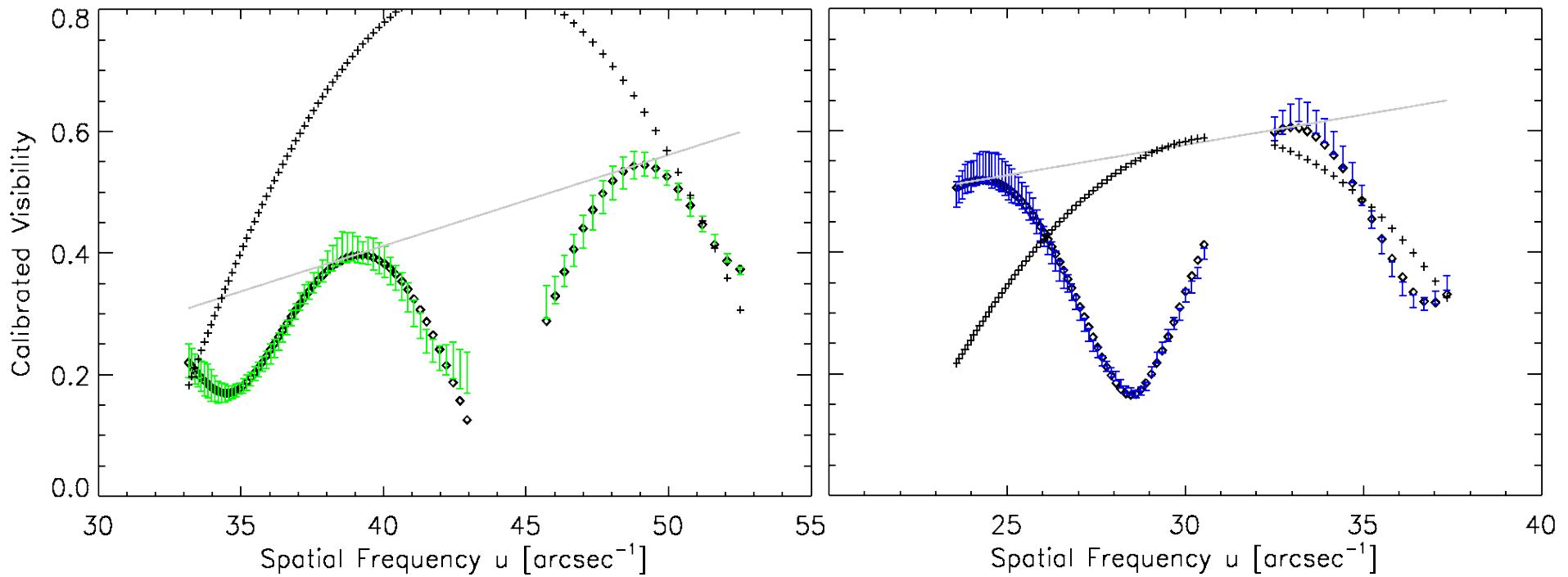
T. A. Rector (University of Alaska Anchorage) &  
H. Schweiker (WIYN and NOAO/AURA/NSF)



# The Grid



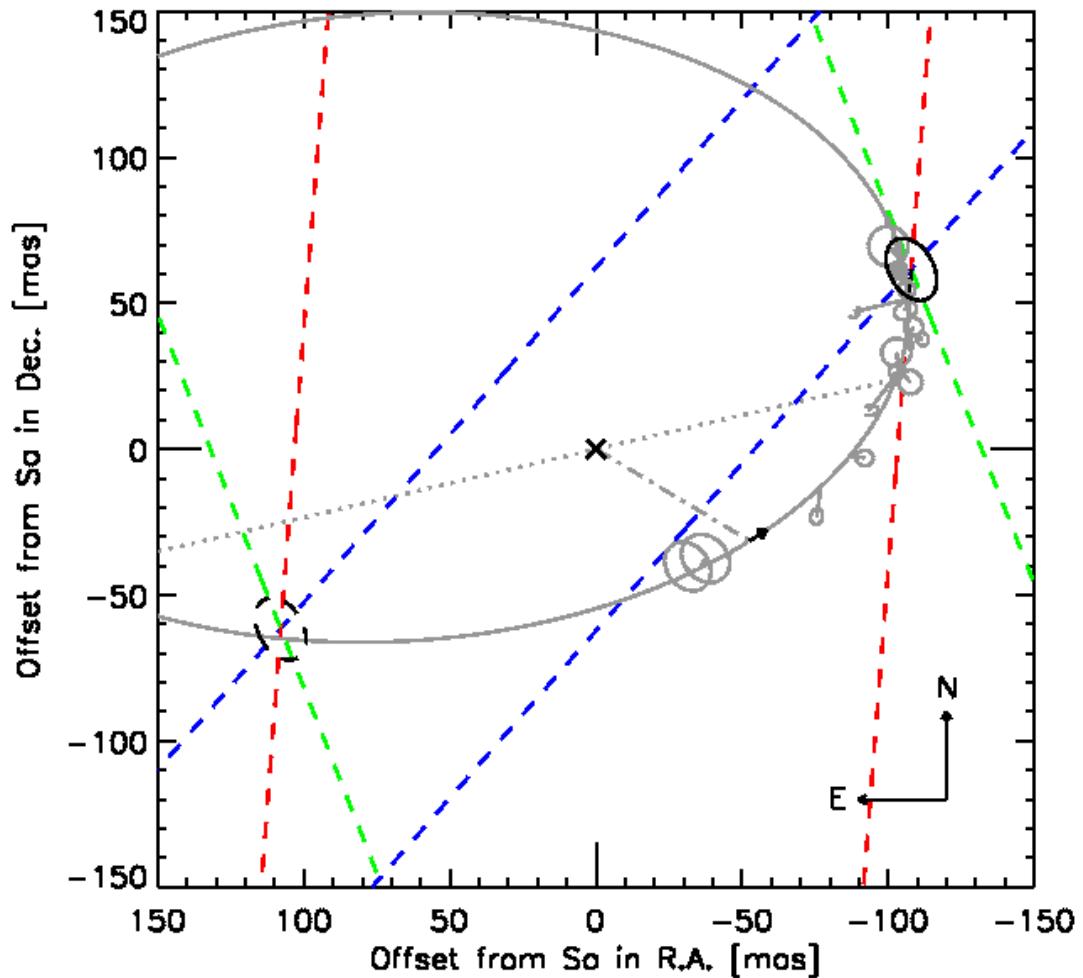
# The Binary Signal



$$V_{\text{fit}}(u) = V_0(u) \cdot \frac{\sqrt{1 + f^2(u) + 2f(u) \cos[2\pi u s(u)]}}{1 + f(u)}$$

$V_0(u) = a_0 + a_1 u$   
 $f(u) = f_0 + f_1 u + f_2 u^2, \quad f(u) < 1$   
 $s(u) = s_0 + s_1 u$

# The Relative Position of T Tau Sb

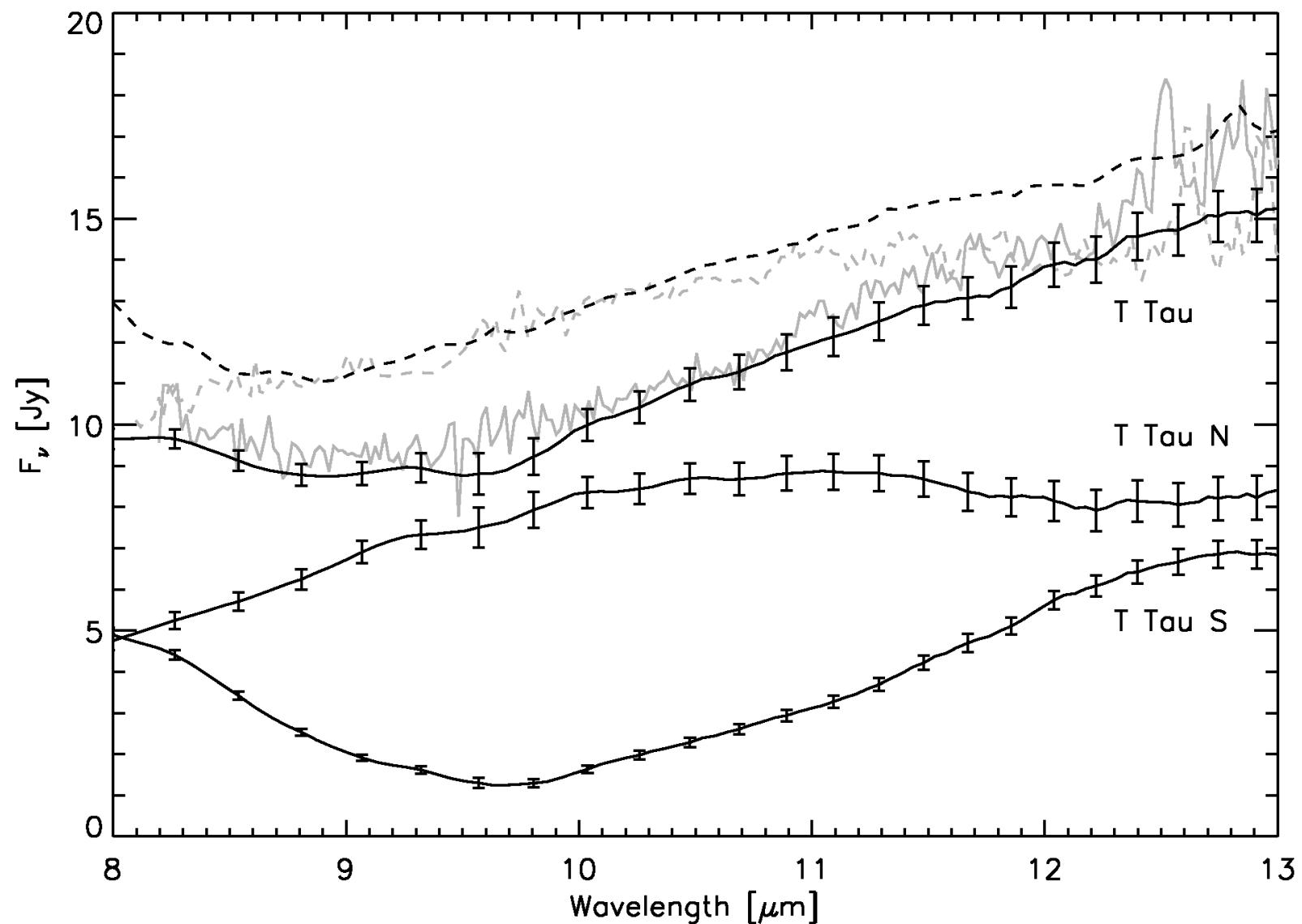


$$s \approx 103.0 \pm 1.2 \text{ mas} (87.6^\circ)$$

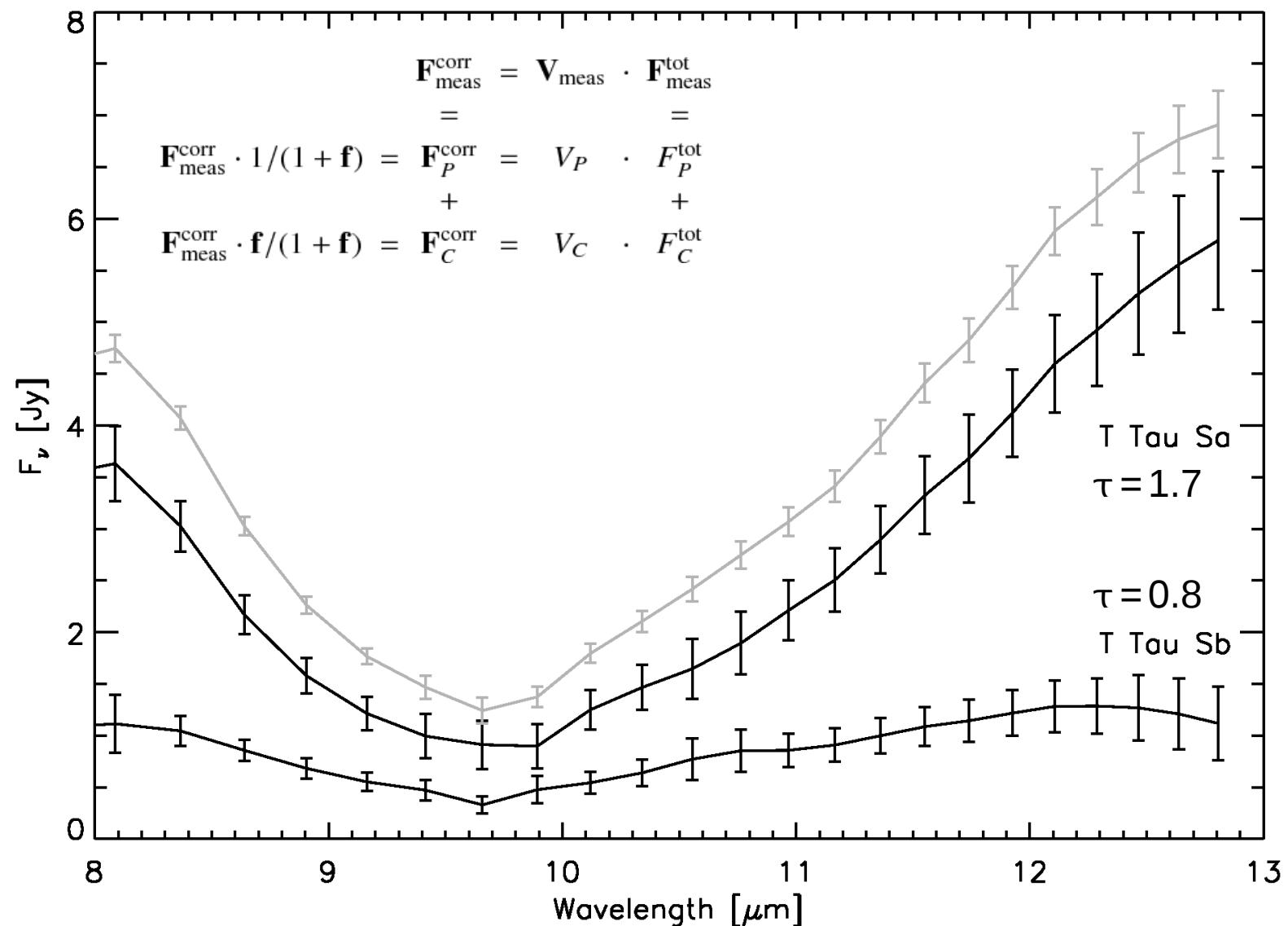
$$s \approx 123.0 \pm 5.9 \text{ mas} (111.4^\circ)$$

$$\Rightarrow 124.3 \pm 7.6 \text{ mas} @ 299.7 \pm 5.3^\circ$$

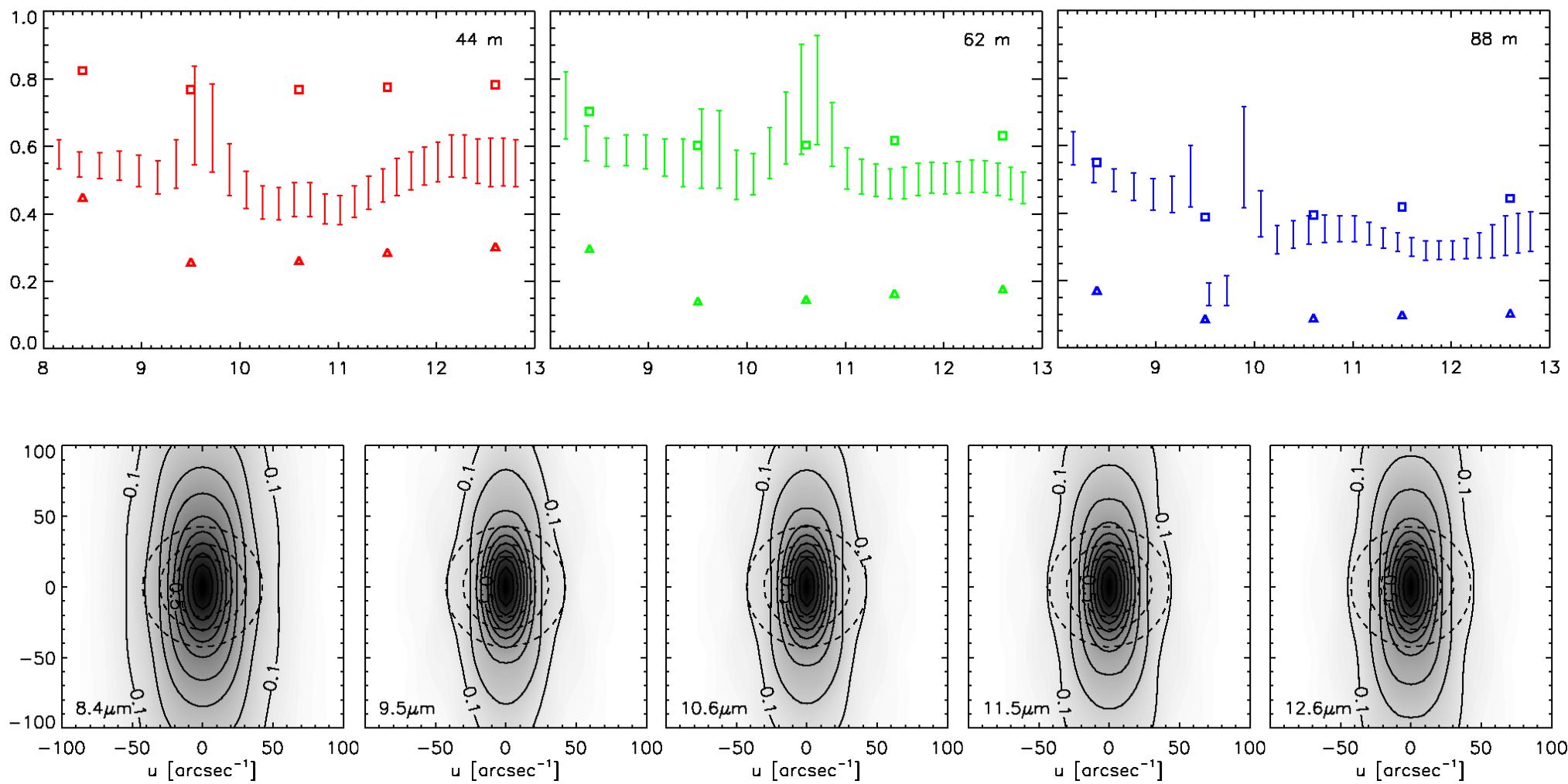
# Separating the Spectra



# Separating the Spectra



# Model for T Tau Sa

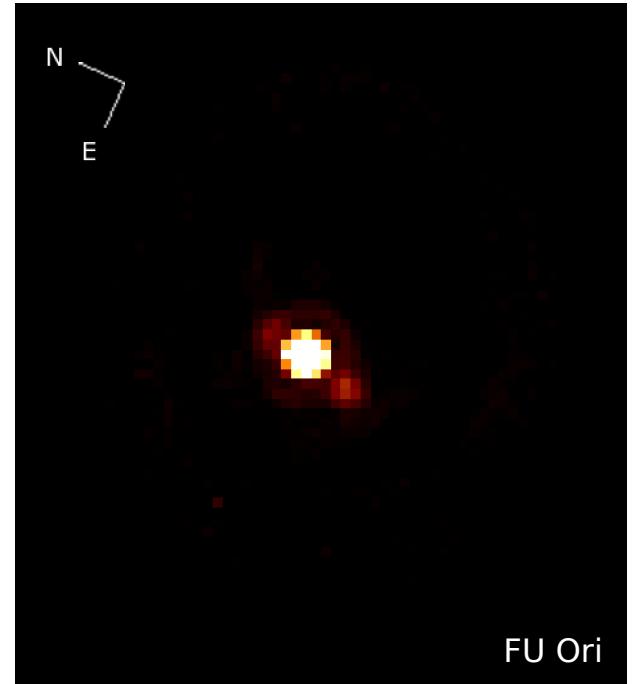
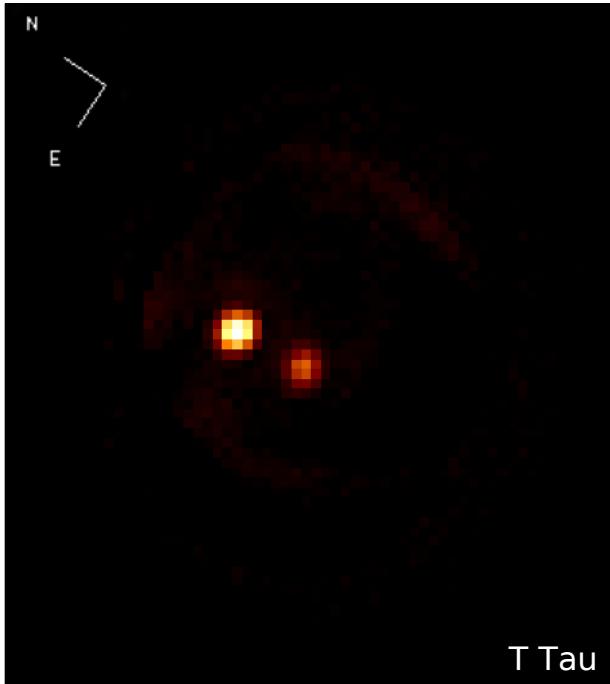
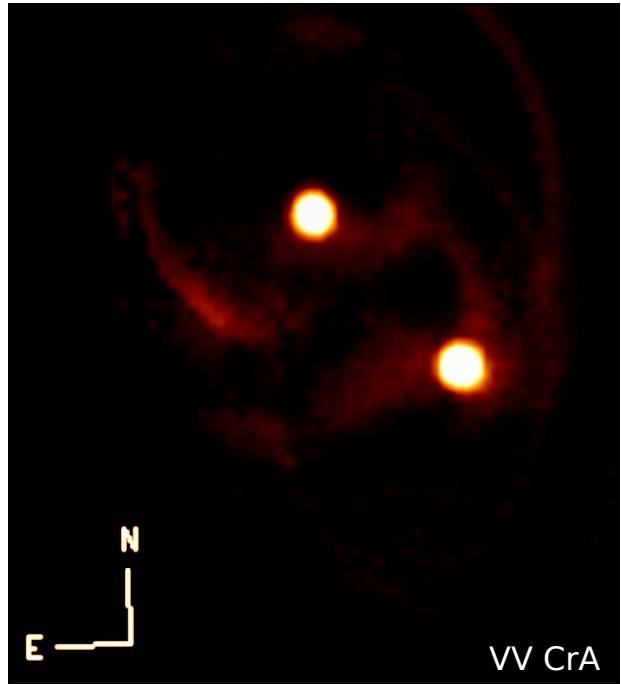


A landscape photograph of a valley at sunset. The sky is filled with warm, orange and yellow hues, transitioning into a darker blue at the bottom. In the center, a bright sun is partially hidden behind a range of mountains. The foreground is a dark, hilly terrain.

Science V

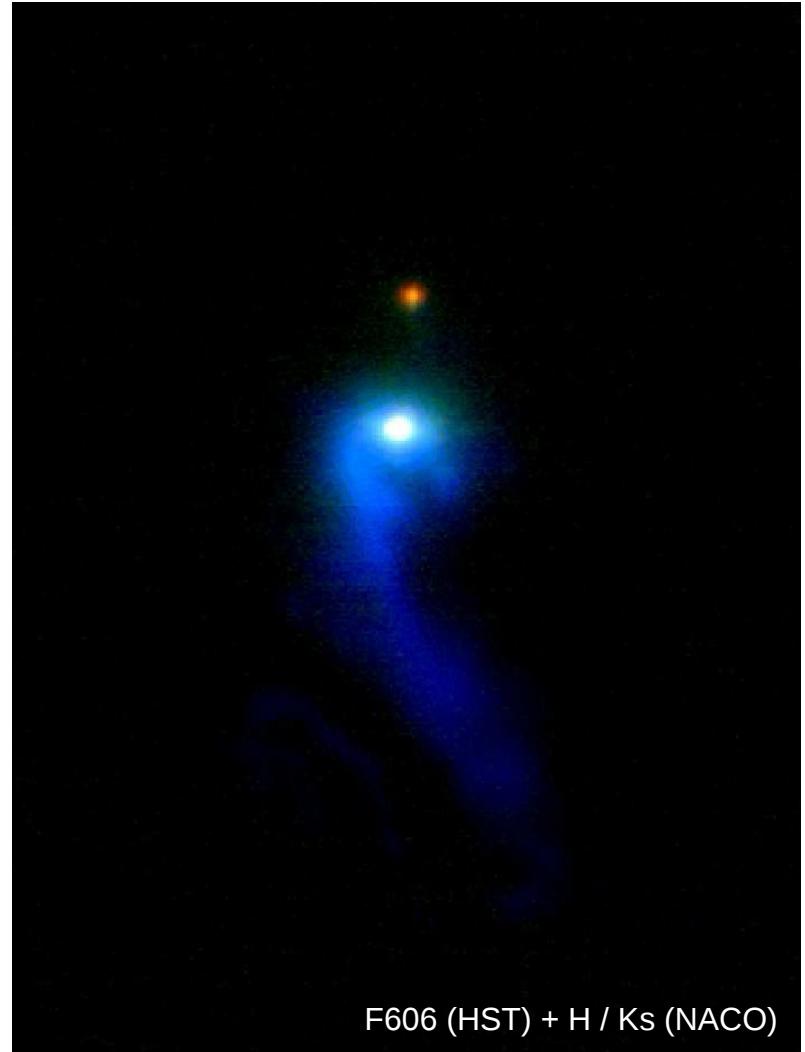
# **Binaries in the Mid-Infrared**

# “Family Portraits”

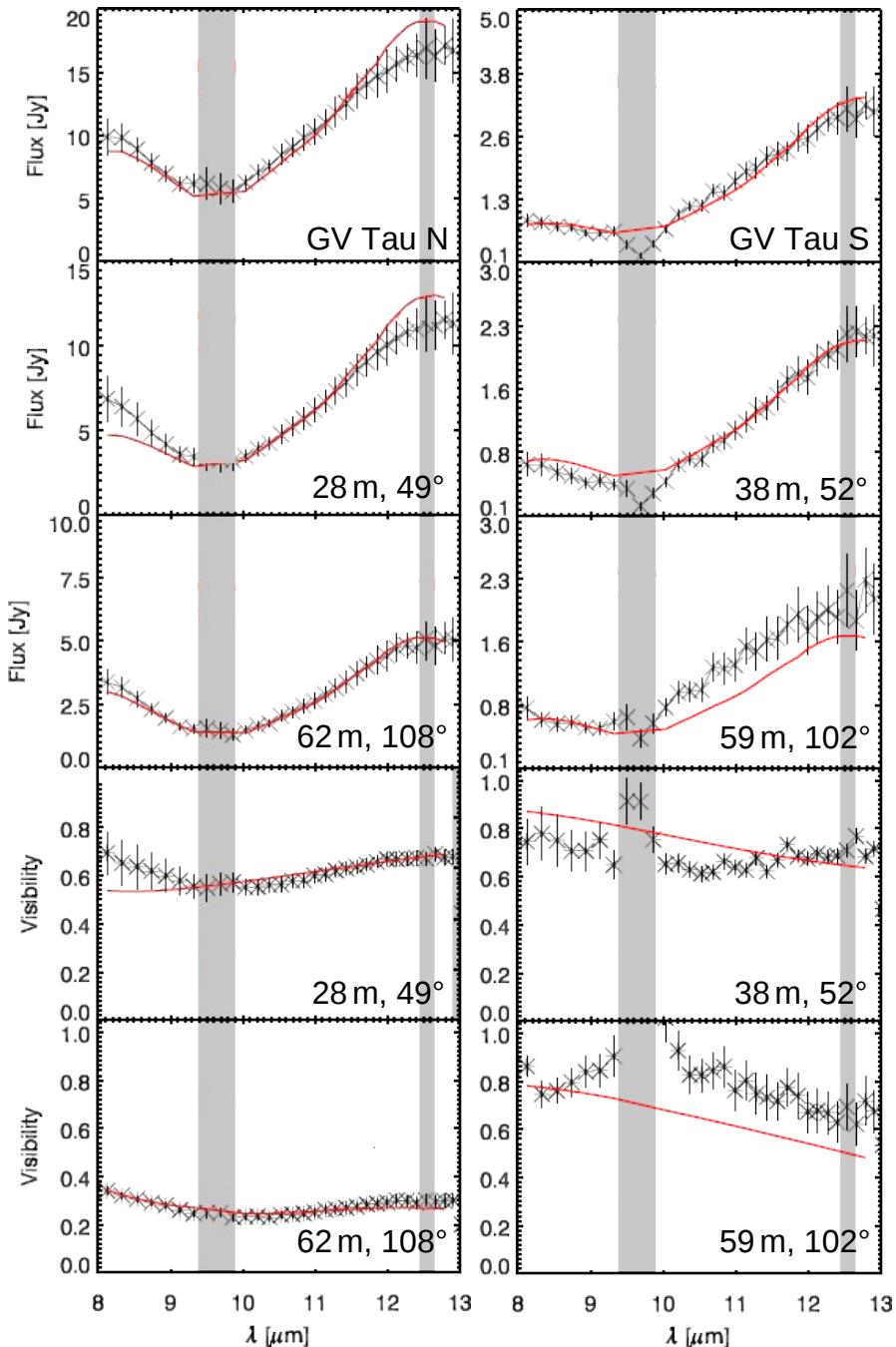


# GV Tau – Another Infrared Companion

- binary separated by 1.2“
- distance of 140-160 pc
- variable on short timescales due to
  - inhomogeneities in the circumstellar material around the southern component?
  - variable accretion of the northern component?
- presence of a circumbinary envelope suggested

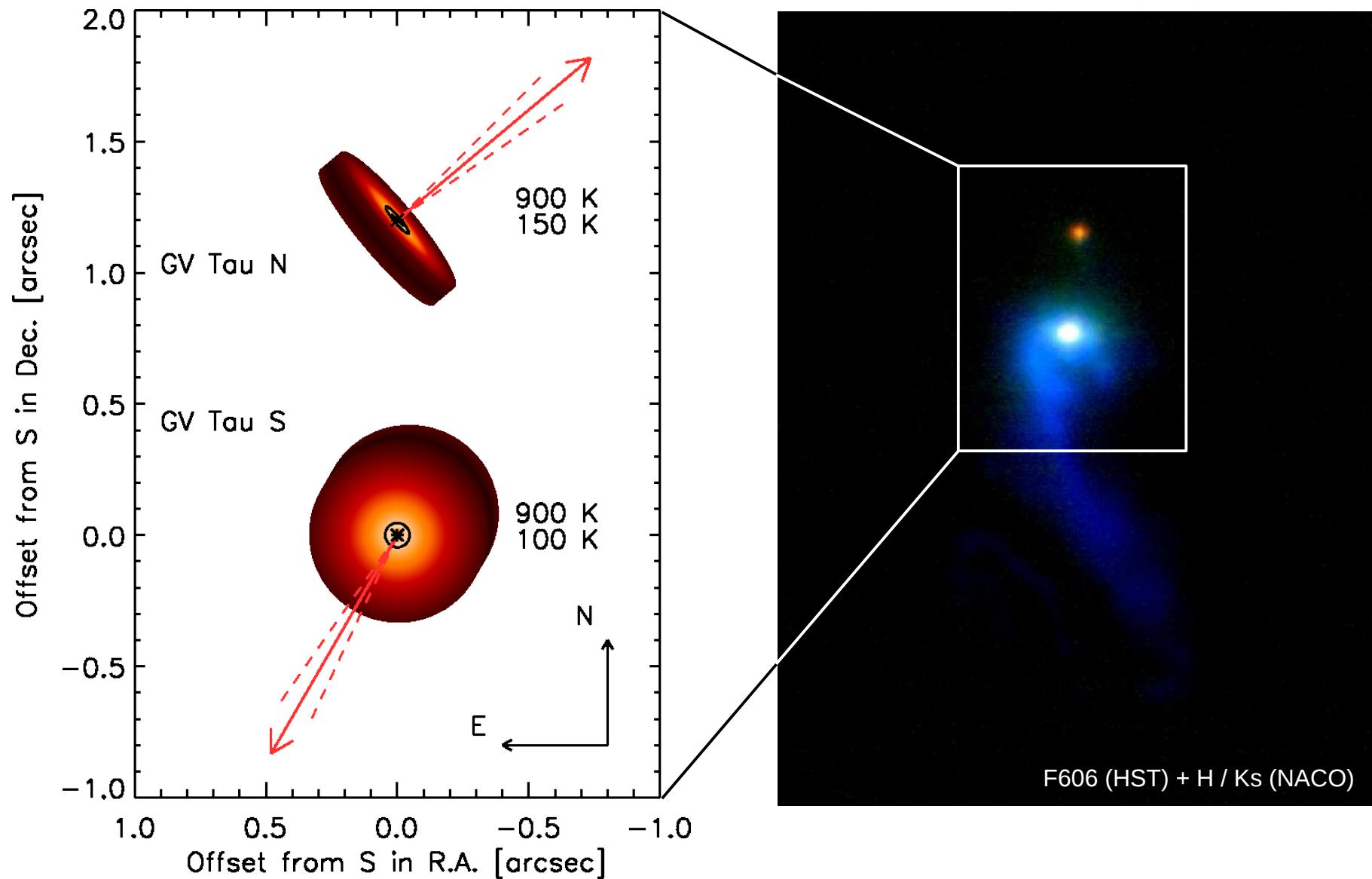


F606 (HST) + H / Ks (NACO)



	<b>GV Tau N</b>	<b>GV Tau S</b>
$r_1$ [AU]	$1.5 \pm 0.5$	$1.0 \pm 0.5$
$T_1$ [K]	$900 \pm 100$	$900 \pm 300$
$r_2$ [AU]	$10 \pm 2$	$7 \pm 3$
$T_2$ [K]	$150 \pm 50$	$100 \pm 50$
$i$ [deg]	<b><math>80 \pm 10</math></b>	<b><math>10 \pm 5</math></b>
PA [deg]	$50 \pm 20$	$50 \pm 20$
$A_V$ [mag]	$13 \pm 4$	$19 \pm 4$

# GV Tau – Another Infrared Companion



# SVS 20 – In the Core of Serpens

- binary separated by 1.5"  
(actually a triple system!)
- distance of about 250 AU

SVS 20 N

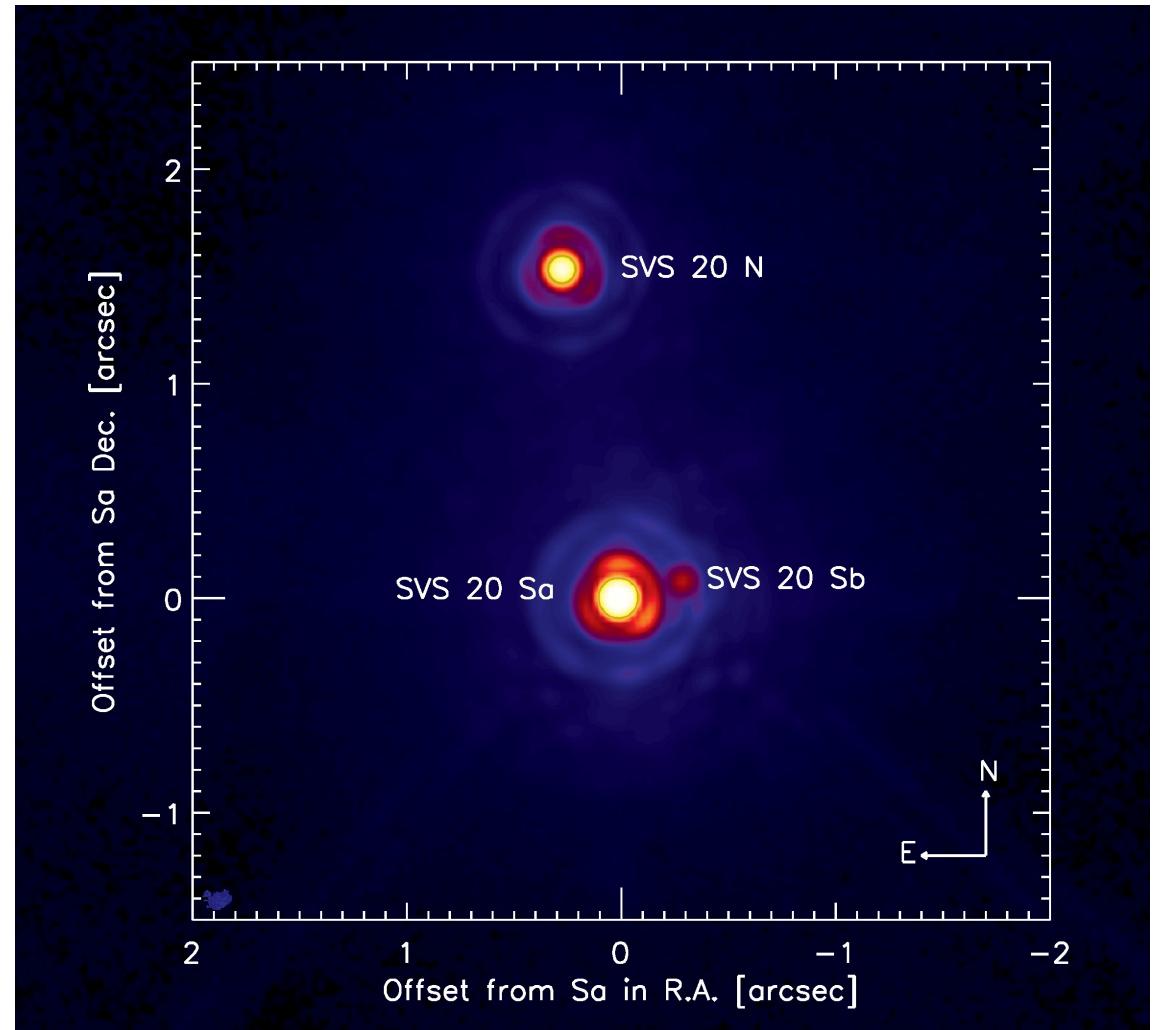
$T = 3300 \text{ K}$

$L = 0.9 L_\odot$

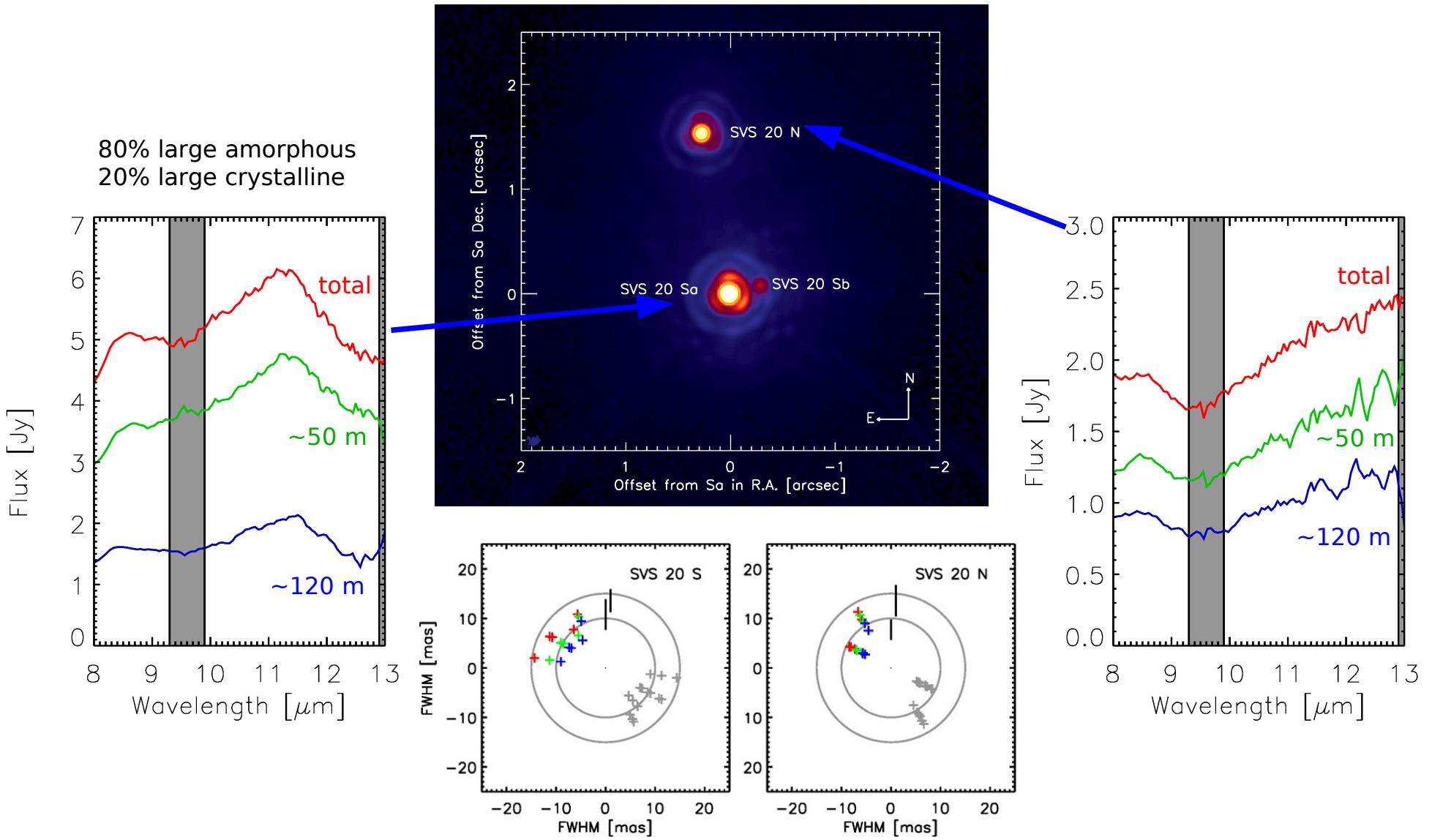
SVS 20 S

$T = 6000 - 10000 \text{ K}$

$L = 20 - 80 L_\odot$



# SVS 20 – In the Core of Serpens



A landscape photograph of a sunset over mountains, serving as the background for the title page. The sky is filled with warm, orange and yellow hues from the setting sun, which is partially obscured by the mountain range. The foreground is dark and indistinct.

Epilog

# Beyond Science

10. December 2002

MIDI on siderostats

UT

23h50

Vinal Siderostat

0h 25

o Yet standard acquisition ✓

if well visible = overlay test after recentering - ✓

if visible: friend star template ✓

acquisition ✓

overlay deck beams A,B

3h 15

0h 25

FIRST FRINGES on α Ori I

4h 20

Thanks

UWE \*\*\*

- (2)
- (3)
- (4)

Fringes.  
ε Car

(5)

-0.6.	(6)
-1.6.	(7) FRINGE!
4.	(8)
2-6	(9)

60-

-1 my → -22 arcsec  
Santiago



UT

Star -

8

80 count

2000 frames

9

{ X1: Super Andal.

10 } X2: 5 right on And.

11 } 1000 frames

12 } 1000 frames

13 } 1000 frames

14 } 1000 frames

15 } 1000 frames

16 } 1000 frames

17 } 1000 frames

18 } 1000 frames

19 } 1000 frames

20 } 1000 frames

21 } 1000 frames

22 } 1000 frames

23 } 1000 frames

24 } 1000 frames

25 } 1000 frames

26 } 1000 frames

27 } 1000 frames

28 } 1000 frames

29 } 1000 frames

30 } 1000 frames

31 } 1000 frames

32 } 1000 frames

33 } 1000 frames

34 } 1000 frames

35 } 1000 frames

36 } 1000 frames

37 } 1000 frames

38 } 1000 frames

39 } 1000 frames

40 } 1000 frames

41 } 1000 frames

42 } 1000 frames

43 } 1000 frames

44 } 1000 frames

45 } 1000 frames

46 } 1000 frames

47 } 1000 frames

48 } 1000 frames

49 } 1000 frames

50 } 1000 frames

SNR > 4

→ Super Andal.

→ 5 right Andal.

→ 5 pixels dither.

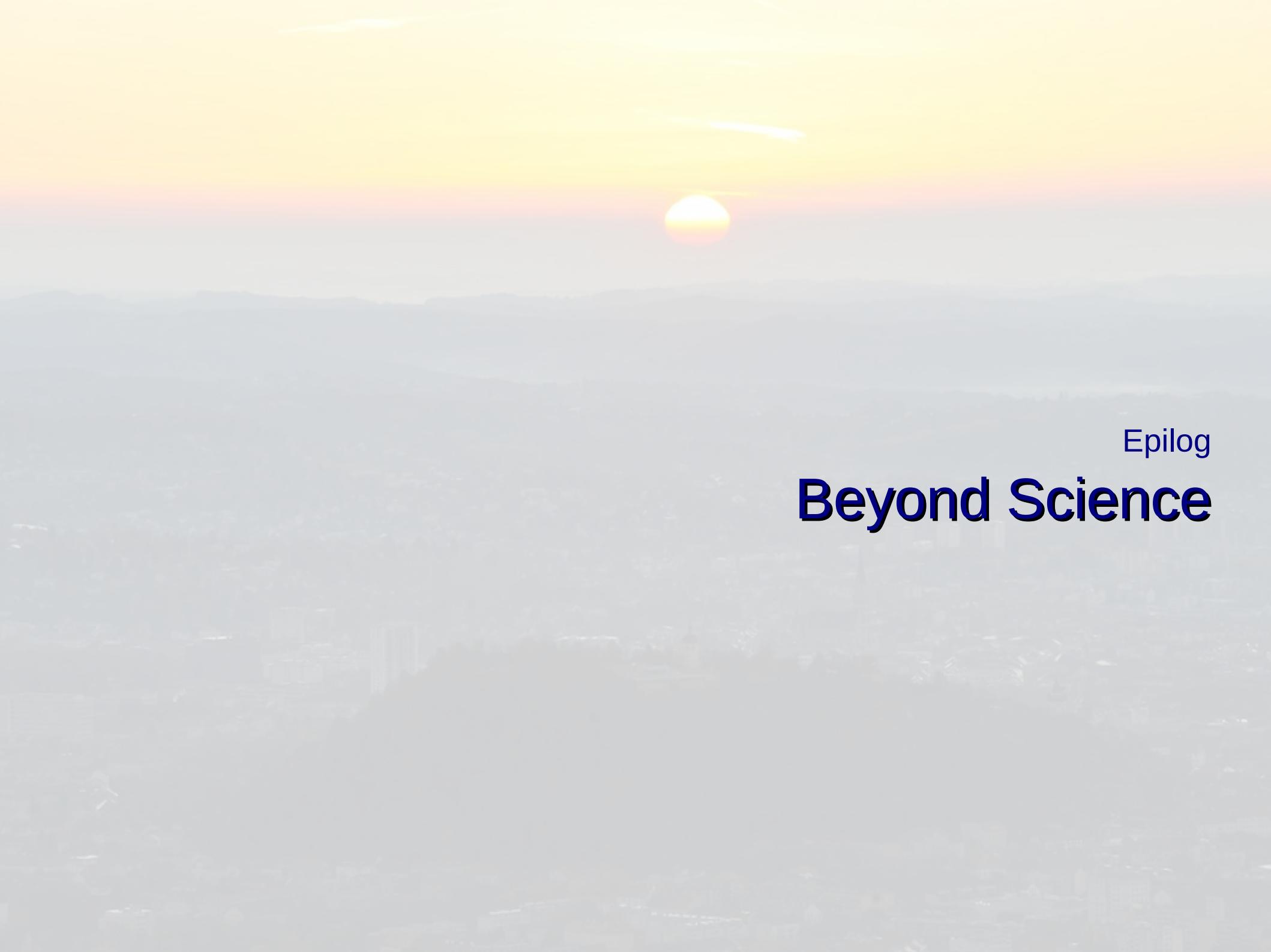
8 / 100

125 → good overlap

⇒

11. December 2002  
"First Fringes on α Ori"

15. December 2002  
"UT-Fringes on ε Car & Z CMa"

A landscape photograph showing a sunset or sunrise over a range of mountains. The sky is filled with warm, orange, and yellow hues near the horizon, transitioning to a darker blue-grey above. The mountains are dark and silhouetted against the bright sky. A large, bright sun is visible in the upper right quadrant, casting a glow across the scene.

Epilog

# **Beyond Science**